VOLUME XXXII NUMBER 5

THE
JOURNAL OF GEOLOGY

July-August 1924

THE RELATION OF THE PHYSICAL PROPERTIES OF NATURAL GLASSES TO THEIR CHEMICAL COMPOSITION[1]

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INTRODUCTION

Purpose and scope.—The natural glasses vary widely in composition, though a large proportion of the known occurrences are rhyolitic. They also show considerable variation in hardness, color, diaphaneity, fusibility, magnetism, solubility, specific gravity, and index of refraction.[2] The writer has observed the physical properties of a large number of specimens of natural glasses of known chemical composition with the hope that simple physical tests might prove almost as satisfactory as chemical analyses in classifying natural glasses.

Nature and occurrence of natural glasses.—All igneous rocks which are not crystalline are called natural glass. If a melt solidifies before its crystallizing-point is reached, the result is natural glass.

[1] This paper was first submitted to the graduate school of the University of Minnesota in partial fulfilment of the requirements for the degree of Master of Science, but it has been very much condensed for publication.

[2] Michael Stark, "Zusammenhang des Brechungsexponenten natürlicher Gläser mit ihrem Chemismus," *Min. u. pet. Mitt.*, Neue Folge, Vol. XXIII (1904), p. 536.

Glasses are best named on the basis of (1) structure, as obsidian, pumice, perlite, tuff; and (2) composition, indicated by the name of the felsitic rock of corresponding composition, rhyolite pumice, dacite perlite, andesite obsidian, etc.

Pitchstones generally have a high content of water. Published estimates[1] are as high as 11 per cent. A study of the analyses of natural glasses published in *United States Geological Survey, Professional Paper 99*, by H. S. Washington, shows that seventeen pitchstones, mostly rhyolitic, average 5.12 per cent water; thirty-five obsidians, presumably rhyolitic, average 1.44 per cent water; a few rhyolitic perlites average about 3 per cent water; eight analyses of pumice show an average water content of 3 per cent.

The range in composition for natural glasses is wide. The published analyses range in silica content from about 40 per cent to 82 per cent. They do not vary, however, so widely as crystalline igneous rocks, if one may judge by analyzed material. There are no glassy representatives of the monomineralic rocks, or segregations. It is therefore a relatively simple matter to show the approximate composition of the series of glasses in a plane diagram.

A number of writers have shown by analyses that natural glasses differ in composition from the related crystalline rocks.[2] Perhaps the most extreme case is shown in a set of analyses made by Ditmar[3] on material from the Dunoon Dike, which as a whole contains only 47.36 per cent silica, while the glassy segregation veins contain 68.05 per cent silica. In general it may be said that glasses are more acid and contain more alkali than related crystalline rock or the crystalline portion of the same rocks, the potash especially dominating over the soda.

[1] Weinschenk and Johannsen, *Fundamental Principles of Petrology* (1916), p. 18; Reinhold Reinisch, *Petrographisches Praktikum*, Part II (1904), p. 22.

[2] J. S. Diller, *Science*, May 30, 1884, p. 562; J. J. H. Teall, *British Petrography* (1888), pp. 42–43; G. F. Becker, *U.S. Geol. Surv., Mon. 13* (1888), pp. 159–61, 153–55; A. Lagorio, "Über die Natur der Glasbasis, sowie der Krystallisationsvorgänge im eruptiven Magma," *Min. u. pet. Mitt.*, Vol. VIII (1887), p. 421; M. A. Lacroix, "Étude minéralogique des produits silicates de l'éruption du Vésuve," *Nouvelles archives du Muséum d'Histoire Naturelle*, Fourth Series, Vol. IX, p. 43.

[3] Ditmar, *Trans. Roy. Soc. Edinburgh*, Vol. XXXV (1888), p. 44.

Alteration and devitrification of glasses result commonly in the development of crystals, but some slight changes may occur before any actual structure becomes visible. The errors resulting from the use of data from such altered rocks are probably slight.

THE DATA

The data used in this paper were obtained from a large number of publications and from personal observations and determinations on a large collection at Minneapolis. For various reasons some of the data had to be rejected. The specific gravities published for six analyzed pumice rocks were obviously too low, for reasons explained in the discussion of the methods of determining specific gravity. Five specimens proved to contain too many crystals. One specimen, which may have been meteoric in origin, seemed to be different from those of terrestrial origin. Data for three other specimens were discarded because the discrepancy was large. Whether the error was in experimental work or simply typographical, it seems clear that these 3 results should not carry much weight against the 115 which agree fairly well among themselves. In two or three cases, the chemical data were obtained by averaging the figures for a certain locality, but this was done only with great caution.

Table I gives a list of specimens and their physical properties. All color data and all properties marked with an asterisk were determined by the writer.

Glasses analyzed or composition estimated:

1. Obsidian, Hrafntinnuhryggur, Krafla, Iceland. F. E. Wright, *Bull. Geol. Soc. Am.*, Vol. XXVI (1915), p. 260.

2. Obsidian (biotite-soda rhyolite of Sitgreave's Peak), San Francisco volcanic field, Arizona. H. H. Robinson, *U.S. Geol. Surv. Prof. Paper 76* (1913), p. 108. The specimen contained about 5 per cent microscopic inclusions and was slightly kaolinized.

3. Riebeckite-soda rhyolite of San Francisco Mountain, Arizona. H. H. Robinson, *op. cit.*, p. 109. The specimen was almost a perfect glass, containing small scattered phenocrysts of orthoclase, apatite, and zircon.

4. Obsidian, Millard County, Utah. W. Cross, *U.S. Geol. Surv., Bull. 168* (1904), p. 168. Not analyzed, but probably represented by analysis 87 or rhyolite glass given by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99* (1917), p. 125.

TABLE I

Specimen No.	Hardness	Color	Color under Microscope	Specific Gravity	Index of Refraction
1	.....	Black	Colorless	2.389	1.488±5*
2	.....	Black	Colorless	2.37	1.490±3*
3	About 5.5*	Gray to black	Colorless	2.38	1.496±2*
4	About 5.5*	Black	Colorless	2.25	1.496±2*
5	6–7*	Gray and black	Gray and brown	2.56	1.505±2*
6	.....	Black	Greenish gray	2.58	1.5340
7	6–7*	Black	Colorless	.....	1.497±3*
8	About 5.5*	Dark brown	Brown	2.87	1.597±3*†
9	About 5.5*	Red and black	Colorless to brown	2.336*	1.488±2*
10	About 7*	Brown to green	Colorless	2.330*	1.492±5*
11	.....	White to yellow	Colorless	2.573*	1.528±4*
12	.....	White	Colorless	2.389*	1.506±2*
13	6–7*	Black	Colorless	2.345	1.498±2*
14	6–7*	Green	Colorless	2.321*	1.497±2*
15	6–7*	Black	Brown	2.728*	1.57 ±3*†
16	About 7*	Black	Brown	2.495*	1.519±4*
17	6–7*	Gray	Colorless	.....	1.497±3*
18	About 5.5*	Black	Brown	2.333*	1.502±3*
19	About 7*	Black	Greenish to brownish gray	2.37	1.498±2*
20	About 5.5*	Black	Pale	2.52	.....*†
21	.....	Gray	Light brown	.....	1.501±1*
22	.....	Gray	Colorless	.....	1.504±2*
23	6–7*	Gray	Colorless	.....	1.497±4*
24	About 7*	Greenish gray	Colorless	.....	1.504±4*
25	6–7*	Black and pearl-gray bands	Colorless	2.202*	1.497±3*
26	.....	Gray	Colorless	.....	1.506±4*
27	6–7*	Black	Colorless	.....	1.48 ±2*
28	.....	White	Colorless	.....	1.516±3*
29	.....	White	Colorless	.....	1.506±5*
30	6–7*	Black	Colorless	.....	1.488±5*
31	6–7*	Black	Colorless	.....	1.483±1*
32	.....	Black, gray and green	Brown	.....	1.527±2*
33	.....	Dark gray-green	Very light green and brown	.....	1.517±6*
34	About 7*	Black	Dark green	.....	1.506±4*
35	.....	Black	Colorless to brownish gray	.....	1.529±5*†
36	.....	Black, yellow, and brown	Brown, yellow, black granules	.....	1.58 ± *†
37	.....	Brown	Brown	.....	1.56 ±1*
38	About 5.5*	Black and gray	Brown	2.85	1.56 ±1*
39	About 5.5*	Black	Colorless, yellow, and brown	2.894*	1.612±9*
40	6–7*	Green	Colorless	2.903*	1.610± *
41	6–7*	Black	Colorless	.....	1.480±2*
42	.....	Black	.....	.....	1.605
43	5.5–6*	Gray	Colorless	.....	1.497±4*
44	6–7*	Red	Colorless	.....	1.488±4*

* Determined by the writer. † Variable in different parts of the specimen.

TABLE I—*Continued*

Specimen No.	Hardness	Color	Color under Microscope	Specific Gravity	Index of Refraction
45....	.....	White to pink	Colorless	2.45	1.488±4*
46....	6–7*	Pearl	Colorless	.....	1.488±3*
47....	About 7*	Pearl to black	Colorless	.....	1.488±4*
48....	6–7*	Pearl-gray with black nodules	Colorless	.....	1.483–* 1.501*
49....	.....	Gray	Colorless	.....	1.506±3*
50....	About 7*	Gray to pink	Few red spots, nearly all colorless	.....	1.506±4*
51....	About 7*	Black	Colorless	.....	1.497±3*
52....	About 5.5*	Green	Colorless	.....	1.497±4*
53....	6–7*	Gray to black	Some very dark green, some colorless	.....	1.511± *†
54....	.....	Dark brown	Dark brown	.....	.....
55....	.....	Brownish gray	Brown to green	.....	1.488±4*
56....	6–7*	Pearl-gray and white	Colorless	.....	1.506±4*
57....	6	.....	.....	2.65–2.70	.....
58....	6–7*	Red	Colorless and pinkish brown	.....	1.496±2*
59....	6–7*	Black	Nearly opaque	.....	1.61 ±1*†
60....	6–7*	Red	Brown, nearly opaque	.....	1.58 ±2*
61....	6–7*	Black	Brown	.....	1.506±4*
62....	.....	Black	Greenish brown	.....	1.57 ±3*†
63....	6–7*	Black	Crystals colorless, glass brown	.....	1.506±5*
64....	6–7*	Black	Colorless	.....	1.497±3*
65....	6–7*	Black	Brown	2.370*	1.504±3*
66....	About 7*	Red and black	Pink, gray, black	.....	1.506±4*
67....	.....	Dull pitch-black	Nearly colorless	.....	1.506±4*
68....	.....	Pink	Pink from hematite	.....	1.50 ±1*
69....	.....	Gray	Colorless	.....	1.506±4*
70....	.....	White	Colorless	2.40	1.4888

* Determined by the writer. † Variable in different parts of the specimen.

5. Dacite, Bear Creek Falls, Shasta County, California. H. S. Diller, *U.S. Geol. Surv., Bull. 150*, No. 80, p. 215. About two-thirds of the specimen was glass.

6. Glass in leucite tephrite (dike in large block), Vesuvius, eruption of 1906. A. Lacroix, *Nouvelles archives du Muséum d'Histoire Naturelle*, Fourth Series, Vol. IX (1907), p. 45.

7. Obsidian, Conca Cannas, Uras, Mount Arci, Sardinia. Probably represented by analysis given by H. S. Washington, *Amer. Jour. Sci.*, Third Series, Vol. XXXVI (1913), p. 582. The specimen contained many opaque crystallites.

8. Basic pitchstone ash, northeast of Meriden, Massachusetts. B. K. Emerson, *Bull. Geol. Soc. Am.*, Vol. VIII (1897), p. 59.

9. Red obsidian, Obsidian Cliff, Yellowstone National Park. J. P. Iddings, *U.S. Geol. Surv., Seventh Ann. Rept.* (1888).

10. Pitchstone, Meissen, Saxony. A. Lagorio, *Min. u. pet. Mitt.*, Vol. VIII (1887), p. 421. Two samples from same locality differ slightly.

11. Lapilli andesitic, Pelée Volcano, Martinique, Heilprin. The analysis used for this specimen is the average of thirteen analyses of andesite fragmentals reported by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99* (1917). The analyses were very much alike.

12. Rhyolitic pumice, Mono Lake, Mono County, California. Waldemar Lindgren, *U.S. Geol. Surv., Bull. 150* (1898), No. 59, p. 149. This is a very pure glass, containing only 1 to 2 per cent biotite and 1 to 2 per cent feldspar.

13. Black obsidian, Obsidian Cliff, Yellowstone National Park. J. P. Iddings, *U.S. Geol. Surv., Seventh Ann. Rept.*, pp. 282–88. Very nearly pure glass.

14. Pitchstone, Silver Cliff, Colorado. W. Cross, *U.S. Geol. Surv., Seventeenth Ann. Rept.* (1897), Part II, p. 320. Specimen contains very few crystals. Cross describes color as yellow, green, brown, red, and black. The specimen examined was green.

15. Tachylite, Bobenhausen, Hesse, Germany. Probably represented by analysis given by Lagorio, *op. cit.*, No. 90, p. 492.

16. Trachyte obsidian (phonolitoid), Gough's Island, South Atlantic. L. V. Pirsson, *Amer. Jour. Sci.*, Third Series, Vol. XLV (1893). The rock contains many pores, but very few crystals. Specific gravity, as published, 2.21, evidently erroneous.

17. Perlite, Deer Creek Meadows, Tehama County, California. Probably represented by this analysis which is given by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99* (1917), No. 18, p. 81.

18. Pitchstone, Arran, Scotland. Not analyzed, but composition used is the average of two analyses from that locality listed by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99*. Under the microscope the specimen is dusty with crystallites. Two specimens from same locality were observed which differed slightly. The index of refraction and specific gravity given are averages of the two.

19. Rhyolite pitchstone, Checkerboard Creek, Montana. L. V. Pirsson, *U.S. Geol. Surv., Bull. 139* (1896), pp. 124–25.

20. Glass from leucite tephrite, Vesuvius, eruption of 1906. M. A. Lacroix, *op. cit.*, p. 43.

21. Andesitic tuff, Stillwater Creek, California. J. S. Diller, *U.S. Geol. Surv., Bull. 150*, No. 79, p. 212. Seventy-five per cent glass, containing hornblende and feldspar and opaque crystals.

22. Glass base from dacite Lassen Peak, California. Hague and Iddings, *Am. Jour. Sci.*, Third Series, Vol. XXVI (1883), p. 232. Specimen contained radiating needle-like microlites.

23. Rhyolitic perlite, Yellowstone National Park. J. P. Iddings, *U.S. Geol. Surv., Bull. 150*, No. 61, p. 154. About 1 per cent of the rock is composed of quartz grains.

24. Rhyolite glass, west slope of Burton Peak, 50 feet below summit, Bullfrog, Nevada. W. H. Emmons, *U.S. Geol. Surv., Bull. 407* (1910), No. 12. Analysis is for rhyolite No. 15 which, according to *Bull. 407*, is similar to No. 12. The rock is about 95 per cent glass, containing crystals of quartz, orthoclase, hornblende, hypersthene, and augite.

25. Obsidian, Forgia, Vecchia Lipari, Aeolian Islands. A. Bergeat, *Ab. Much. Ak.*, Vol. XX (1899), p. 111. Banded liparite obsidian with black and pearl-gray bands.

26. Rhyolitic tuff, Belshaw's Ranch, John Day Basin, Oregon. F. C. Calkins, *Univ. Cal. Dept. Geol., Bull. 3* (1902–4). Specimen was estimated to contain about 98 per cent glass.

27. Rhyolitic obsidian, Mono Lake, California. Waldemar Lindgren, *op. cit.*, p. 151.

28. Volcanic dust, Gallatin Valley, Gallatin County, Montana. A. C. Peale, *U.S. Geol. Surv., Folio 24;* also J. P. Iddings, *U.S. Geol. Surv., Bull. 150*, p. 146. Specimen was slightly kaolinized, but free from microlites.

29. Volcanic ash, Ravalli County, Montana. J. P. Rowe, *Univ. Mont. Bull. 17* (1903), p. 9. The average of three analyses was used as an estimate of the composition.

30. Scoria. The specimen is almost certain to have the composition given for scoriaceous rhyolite by Russell, *U.S. Geol. Surv., Eighth Ann. Rept.*, p. 380.

31. Obsidian, Iceland. The average of five analyses of obsidians from Iceland, taken from *U.S. Geol. Surv., Prof. Paper 99*, was used as an estimate of the composition of this specimen.

32. Trachite pumice, Arso Stream, Arso, Ischia, Naples, Italy. The analysis used is the third analysis by H. S. Washington, *Amer. Jour. Sci.*, Fourth Series, Vol. VIII (1899), p. 290, which probably represents the specimen examined.

33. Glassy pantellerite, Pantelleria, Italy. H. S. Washington, *Jour. Geol.*, Vol. XXI (1913), p. 706. The average of analyses A, B, C, and D, is here used as an estimate of the composition of the specimen, which is about 25 per cent crystalline.

34. Dacite pitchstone. Dike near shore of Isle of Eigg, Scotland. The composition of the specimen is somewhat doubtful, but the analysis given by J. W. Judd, *Quart. Jour. Geol. Soc. London*, Vol. XLVI (1890), p. 379, is used as an estimate. Under the microscope the powdered rock appeared to be about 25 per cent crystalline.

35. Dacite vitrophyre, 20 miles west of Kelvin, Arizona. Composition doubtful, but estimate was made from one analysis published in *U.S. Geol. Surv., Prof. Paper 12*, p. 92, and from ten analyses published by H. H. Robinson, *op. cit.* The specimen contained about 60 per cent glass.

36. Ash from Vesuvius, eruption of 1886. The composition is estimated from sixteen analyses of ash and lava from the various eruptions of Vesuvius which are published by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99*. Some of the rock was opaque.

37. Palagonite, basalt tuff, southwest base of Punch Bowl, Oahu, Hawaiian Islands. Composition estimated from three analyses from this locality published by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99*. The rock is said to contain 5 to 10 per cent calcite and is partly oxidized.

38. Tachylite (basalt glass), Giessen, Hesse, Germany. Composition estimated from eight analyses published by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99*. The specimen was about 15 per cent crystalline.

39. Kilauea lava (basaltic), Kilauea, Hawaii. Composition estimated from ten analyses of Kilauea lava published by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99*. Another specimen, "Pele's hair," had the same index of refraction.

40. Basalt glass, Mount Aetna, Sicily. Composition estimated from seven analyses of basalt from Mount Aetna published by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99*. The specimen was entirely glass.

41. Rhyolite obsidian, Mono Lake, California. Composition estimated from two analyses published by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99*.

42. Lava dipped from Halemaumau Kilauea Crater, Hawaii. Day-Shepherd. *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), p. 586. Merwin de-describes the glass as follows: "Glass with 1 per cent feldspar and trace of crystals either magnetite or pyroxene. Index 1.605, lining of bubbles slightly higher."

43. Perlite, Uras, Mt. Arci, Sardinia. H. S. Washington, *Amer. Jour. Sci.*, Third Series Vol. XXXVI, (1913), p. 582. Not analyzed, but composition is probably represented by this analysis.

44. Obsidian rhyolite. Transcaucasia, Armenia. Composition doubtful. Estimated from two analyses published by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99*.

45. Andesite pumice, Krakatoa, Straits of Sunda. Composition estimated from eight concordant analyses published by H. S. Washington, *U.S. Geol. Surv., Prof. Paper 99*. The specific gravity is averaged from specific-gravity data given with the analyses.

The following is a list of labeled specimens which were examined but for which no chemical data were available:

46. Garnet-bearing obsidian, Shimeshima, Province of Bungo, Japan.

47. Rhyolite obsidian, Arrowhead, Kern County, California.

48. Perlite, Chaffee County, Colorado. The specimen contains small, black, round nodules of glass which have a lower index than the surrounding glassy matrix.

49. Rhyolite perlite, Hlinik, Hungary.
50. Pitchstone, Elbingerode, Hartz Mountains, Germany.
51. Pitchstone, east of Las Cruces, New Mexico.
52. Pitchstone, resinous green, Georgetown, Colorado.
53. Trachytpechstein, Hlinik, Hungary.
54. Obsidian from trachyte tuff, Procida Ponta di Ricciola.
55. Trachyte (nearly all glass), foot of Monte Novo, near Naples, Italy.
56. Perlitic andesite, Galetnek, Hungary.
57. Tachylite, of Klein-Priesen, Bohemia. (Data published in Boricky's *Petrog. Studien Böhmens*, Vol. II [1874], pp. 182–210.)
58. Rhyolite obsidian, Teotihuacan, Mexico.
59. Tachylite on basalt dike, Kildonon, Isle of Eigg, Inner Hebrides, Scotland.
60. Scoria, Ice Springs Craters, Millard County, Utah.
61. Tachylite, corner New Mexico, Arizona, Mexico.
62. Crust of lava, Vesuvius, 1858.
63. Perlite andesite pumice, Hlinik, Hungary.
64. Andesite, Hart, Nevada.
65. Rhyolitic obsidian, Hallsheivedal ved Skviddal, Eastern Iceland. (The specimen had no label and the name was assumed from the index of refraction and specific gravity.)
66. Pitchstone porphyry spherulites, Spechtshausen, near Tharand, Saxony.
67. "Glassy basalt," Ani, Transcaucasia, Russian Armenia. (Obtained from the American Museum of Natural History and named by E. C. Hovey. The index of refraction is not that of a basalt glass.)
68. Rhyolite to dacite tuff, south of Buffalo Peak, Colorado.
69. Andesitic pumice, Bridge River District, British Columbia.
70. Natural glass of Andesite, Mount Pelée, Martinique. (Data given by M. A. Lacroix, *La Montagne Pélee et ses éruptions*, Paris [1904], p. 511.)

SPECIFIC GRAVITY AND CHEMICAL COMPOSITION

A number of writers[1] have associated a definite range of specific gravity with certain natural glasses, but the generalizations seem to have been made on a relatively small amount of data.

Probably the most satisfactory method of determining specific gravities of natural glasses is by use of the picnometer. The rock should be ground to very fine powder, to eliminate the pores which

[1] Judd and Cole, *Quart. Jour. Geol. Soc. London*, Vol. XXXIX, pp. 462–68; J. J. H. Teall, *op. cit.*, pp. 49–185; A. Lagorio, *loc. cit.*; L. V. Pirsson, *op. cit.*, p. 263. A. Harker, "Tertiary Igneous Rocks of Skye," *Mem. Geol. Surv. United Kingdom* (1904), pp. 338 and 403. On p. 340, Harker notes that with a small range of silica the amounts of iron oxide and water may have more effect on the gravity than silica.

are especially troublesome in some glasses. As long ago as 1880, Cohen[1] noted that the fine pores in some glasses could scarcely be removed well enough to give good values. More recently Michael Stark[2] noted a similar difficulty with "Pele's hair." The writer made several determinations on a specimen of pumice, grinding it to various degrees of fineness, with the result that the specific gravity showed a variation of from 2.249 to 2.389. It was on the basis of these determinations that some of the published results

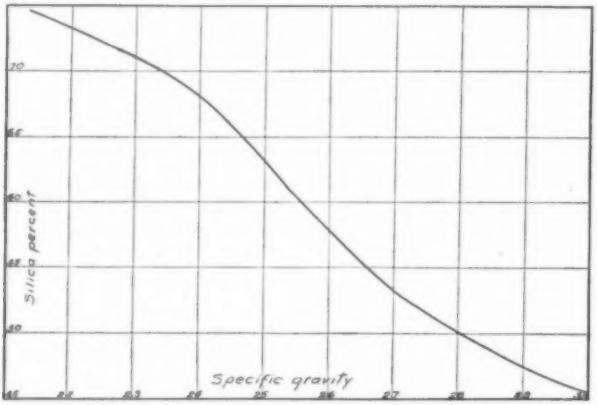

FIG. 1.—Relation of specific gravity to percentage of silica in natural glasses

were eliminated. Care should also be used to note the amount of crystallization in the glass. Zirkel gives in detail the change in gravity as crystalline rocks are melted and cooled to glass,[3] and Rosenbusch[4] gives data on an outcrop that grades from crystalline to glassy diabase.

The various constituents of natural glasses which seem to have a definite relation to specific gravity are represented by Figures 1 and 2. Silica, having a greater significance and a wider range

[1] E. Cohen, *N. Jahrb. f. Min.*, Vol. II (1880), pp. 44–55.

[2] *Op. cit.*, p. 550.

[3] F. Zirkel, *Lehrbuch der Petrographie*, Vol. I, p. 681.

[4] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine*, Vol. II (1908), Part II, p. 118.

than any of the other chemical constituents of natural glasses, is probably best suited to show the relationship. Values for each determination were plotted on the diagram and variations from the curves were calculated. The average error was about 4 per cent. Acid rocks have a higher average content of water than basic rocks, but the gravity is rarely below 2.3 except where the water content is high. Rammelsberg has shown that the removal of 8.49 per cent of water from a glass changed the specific gravity from 2.304

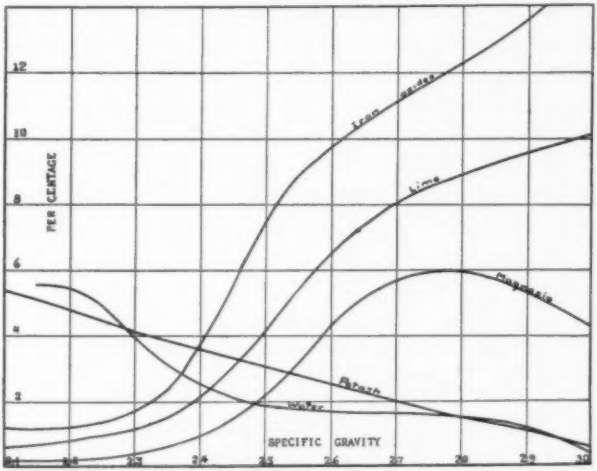

FIG. 2.—Relation of specific gravity to composition of natural glasses. The average error in the curve for iron oxides is less than 1.6 per cent; for potash less than 1.2 per cent; for lime, 1.12 per cent; for magnesia about 1.1 per cent.

to 2.340.[1] Soda and alumina have such a narrow range in percentage that curves showing their relation to specific gravity would be of little value. The average content of soda in natural glasses is 3.7 per cent; the approximate range of alumina is from 13 to 16 per cent.

None of the glasses tested in the present work had a specific gravity above 3.0, but the literature contains a reference to a glass

[1] Rammelsberg, *Zeitschr. d. Deut. Geol. Gesellsch.*, Vol. XX (1868), p. 540.

in New South Wales with a gravity of 3.16 to 3.17 and a suggestion that the composition must be ultra-basic.[1]

INDEX OF REFRACTION AND CHEMICAL COMPOSITION

Very few references are found in the literature to the index of refraction of natural glasses. Stark[2] has made a study of the indices of refraction of natural glasses with reference to the content of silica. He examined 33 specimens, 34 of which had analyses or estimates of composition, and suggested the application of the Gladstone Law[3] for calculating the index from the composition. The writer was able to find very few other papers in which the index of refraction of a natural glass has been mentioned.[4]

The indices of refraction were obtained by the use of the Becke[5] method. Comparisons were made with oils, the indices of which were previously determined in yellow light with a goniometer. This method can be considered accurate only to $\pm .002$,[6] and determinations closer than 0.01 are seldom practical.[7] The indices of

[1] H. Rosenbusch, *op. cit.*, p. 1277, refers to Stonier's description in the records of *N.S. Wales Geol. Surv.*, Vol. III (1893).

[2] *Op. cit.*, pp. 536–50. [3] Gladstone and Dale, *Philos. Trans.*, 1863, p. 337.

[4] F. Zirkel, *Zeitschr. d. Deut. Geol. Gesellsch.* Vol. XIX (1867), p. 750; H. E. Merwin, *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), p. 586; F. E. Wright, "Obsidian from Iceland," *Bull. Geol. Soc. Amer.*, Vol. XXVI (1915), p. 258; H. S. Washington, "The Rhyolites of Lipari," *Amer. Jour. Sci.*, Vol. L (1920), pp. 446–62; A. Lacroix, *Nouvelles archives du Muséum d'Histoire Naturelle*, Fourth Series, Vol. IX (1907), p. 45; F. Rinne, *N. Jahrb.*, Beilage-Band, Vol. XXXIX (1914), p. 402. H. Rosenbusch, *op. cit.*, p. 775.

The textbooks on optical mineralogy give indices of refraction for artificial glasses produced by melting rocks, but it is uncertain how well such results apply to natural glasses. See, for example, Winchell, *Elements of Optical Mineralogy*, p. 424, where the indices of refraction are given in column beside the percentage of silica. The data agree closely with Fig. 3, but include figures for glasses not found in nature.

Since this paper was submitted for publication Tilley has issued a discussion with a small amount of new data and some careful calculations, in the *Mineralogical Magazine* for March, 1922.

[5] F. Becke, "Über die Bestimmbarkeit der Gesteinsgemengteile auf Grund ihres Lichtbrechungsvermögens," *Sitzb. Wien. Akad.*, July, 1893.

[6] W. E. Ford, "Chemical, Optical, and Other Physical Properties of the Garnet Group," *Amer. Jour. Sci.*, Vol. XL (July, 1915), p. 36.

[7] H. E. Merwin, "Physics," *Jour. Wash. Acad. Sci.*, Vol. III, No. 2 (January 19, 1913), p. 36.

glasses range, however, from 1.48 to 1.62 (Stark reports a single sample with index 1.67), so that distinctions are easily made.

Due to weathering, partial oxidation, and actual differences in chemical composition resulting from contact with local agencies, the indices of refraction are likely to show considerable variation in a single specimen. In practice, determinations should be made from several different parts of a specimen or exposure. This is

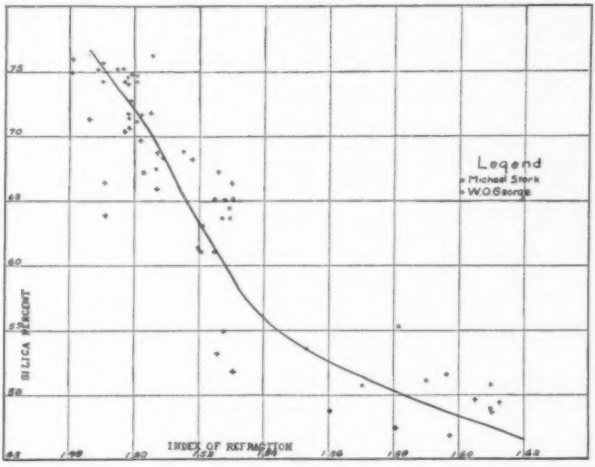

FIG. 3.—Relation of the index of refraction to the percentage of silica in natural glasses.

especially true of the basic rocks. The writer has not observed, however, any variations in those rocks which under the microscope appear to be pure glass and uniform in color.

The relation of the index of refraction of natural glass to the silica content is shown in Figure 3. After drawing the silica-index curve on the basis of all the specimens examined, the amount of variation from the curve was calculated in percentage for each specimen. It was found that those specimens for which reliable analyses were obtained had a maximum error of 8 per cent, an average error of 2 per cent.

The potassium content of the available specimens is shown in Figure 4. The average variation from the curve for 47 specimens is less than 1.1 per cent. For the best data on iron oxides, the average error was 1.4 per cent; on magnesia content, the average error was 0.52 per cent; on lime content, the average error was 0.62 per cent. Water content is so erratic and apparently so little related to index of refraction that a curve showing the relation

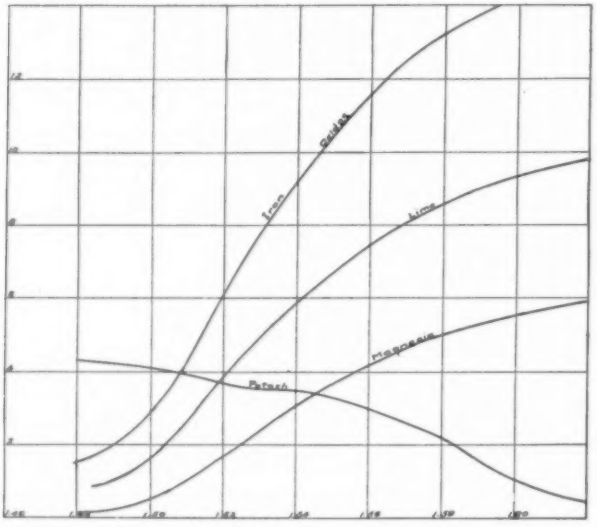

FIG. 4.—Relation of index of refraction to composition of natural glasses

would be of little value. As shown above, curves are not needed for soda and alumina.

Comparison of the two methods.—The index-of-refraction method and the method by specific gravity are compared in Table II. The figures given as "Average Error" represent the amount of variation from the curve.

The amount of data for specific gravity far exceeds that for the index of refraction, but the estimates probably have about the same degree of accuracy.

Relation of index of refraction to specific gravity.—Figure 5 shows that for most samples a certain index of refraction indicates a particular specific gravity.[1] The components of natural glasses are too numerous to allow accurate correlation, but two things are

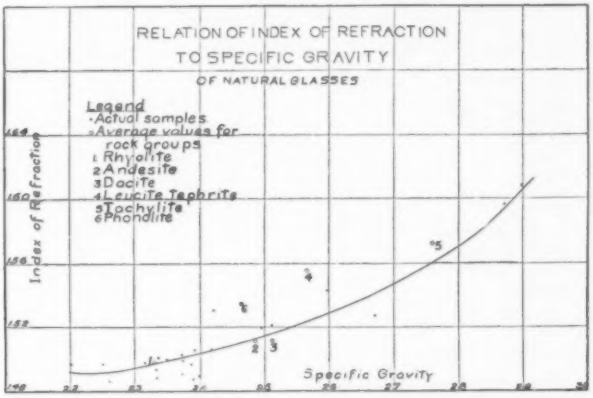

FIG. 5.—Relation of index of refraction to specific gravity of natural glasses

noteworthy: (1) *the points much above the curve represent alkalic rocks;* (2) *the points much below the curve represent partially crystalline rocks.*

TABLE II

	By Specific-Gravity Curves		By Index-of-Refraction Curves	
	Number of Specimens	Average Error	Number of Specimens	Average Error
		Per cent		Per cent
Silica	94	4.0	46	3.4
Iron oxides	98	1.6	43	1.55
Potash	95	1.2	47	1.07
Lime	104	1.1	46	1.14
Magnesia	104	1.1	46	0.38

The figures in Tables III and IV represent the average values for all available data including those determined by the writer.

[1] But see Gladstone and Dale, *loc. cit.*

Alkalic glasses.—Examination of the curve showing the relation of the index of refraction to the specific gravity reveals that most of the points above the curve represent alkalic rocks. This is especially true of glasses ranging from 2.4 to 2.6 in specific gravity.

TABLE III

Collector's or Author's Name of Rock	Average Specific Gravity	Range Recorded
Obsidian or rhyolite glass	2.323	2.13–2.42
Pitchstone	2.335	2.22–2.51
Perlite	2.346	2.23–2.39
Pumice	Evidently data	are erroneous
Dacite	2.505	2.45–2.55
Trachite	2.411	2.25–2.60
Andesite	2.489	2.37–2.67
Leucite tephrite	2.562	2.52–2.59
Tachylite, scoria, diabase and basalt glass Palagonite	2.757	2.50–2.99

The acid rocks having a specific gravity below 2.4 show little range in alkali content, but those glasses having a specific gravity from 2.4 to 2.6 range from 4 to 15 per cent in alkalies. In this group, the rocks having an alkali content below 8 per cent have an average

TABLE IV

Collector's or Author's Name of Rock	Average Index of Refraction	Range Recorded
Obsidian or rhyolite glass	1.492	1.48 –1.51
Pitchstone	1.500	1.492–1.506
Perlite	1.497	1.488–1.506
Pumice	1.497	1.488–1.506
Dacite	1.511–	1.504–1.529
Trachite	1.512–	1.488–1.527
Andesite	1.512–	1.489–1.529
Leucite tephrite	1.550	1.525–1.580
Tachylite, scoria, diabase and basalt glass Palagonite	1.575–	1.506–1.612

index of refraction of 1.510; those above 8 per cent in alkali content have an average index of refraction of 1.522.

It may be suggested that a determination of both the index of refraction and the specific gravity may identify the rock more

closely than either determination used alone. If, after determining both the index of refraction and the specific gravity, it is found that the index of refraction suggests a more basic rock than is indicated by its specific gravity, the glass may be suspected of being alkalic. The lack of sufficient data and the variability as to the content of iron, particularly as to its state of oxidation, make it impossible to plot the distinctions with much accuracy. The rarity of alkalic glasses, however, makes it generally safe to rely on either property that is most conveniently determined.

OTHER PHYSICAL PROPERTIES

The hardness is rarely mentioned in a petrographic description of natural glass.[1] The glasses which have a hardness of 5.5 to 7 seem to range from basalt to rhyolite, and determinations of hardness seem to be of little value. There is a possible exception, however, in pitchstones. Most of the pitchstones examined had a hardness of 7 or greater, which is rather surprising because most pitchstones have a relatively high content of water, and hydrous minerals are commonly softer than their anhydrous equivalents. None of the glasses examined by the writer had a hardness of 8, and it is doubtful if any natural glasses have a hardness much greater than 7.

Under the microscope most acid glasses are colorless and most basic glasses are colored. Exceptions are too numerous, however, to allow the use of color as a basis of determination. It has been noted by Rosenbusch[2] and probably others that the green colors in natural glasses are inherent in the glass itself, but the blacks and browns are dependent on the presence of dark crystals and crystallites.

Judd and Cole[3] and Teall[4] say that basalt glass may in general be distinguished in thin sections by its opacity. The basalt glass from Mount Aetna (specimen 40) and probably others are exceptions. No generalizations as to the opacity of natural glasses may be made for determinative purposes.

[1] Judd and Cole, *op. cit.*, pp. 450–51.

[2] *Op. cit.*, p. 691.

[3] *Op. cit.*, p. 461.

[4] *Op. cit.*, p. 184.

It is claimed[1] that basalt glasses are more easily fusible than acid glasses, and may be so distinguished. Acid glasses also fuse readily, however, especially if they contain water. They then melt with intumescence, usually to a light-colored bead. The product of fusion of a basalt glass is usually an opaque black-brown or black bead. Although this is a general rule, it is not always true, and a determination on that basis is unreliable.

Undoubtedly, basic glasses are more inclined to be magnetic than acid glasses, but the statement made by Judd and Cole[2] that the striking magnetic properties of basalt glasses enable one to distinguish them from other vitreous rocks is not without exception. A number of basalt glasses were tested by the writer which were not appreciably magnetic.

Although in general basic glasses may be more soluble than acid glasses, the differences in solubility are not such as to warrant their use in classification. Penck,[3] Rosenbusch,[4] and others have argued against any attempts at classification on that basis.

APPLICATION OF DATA

The use of the curves (Figures 1–4) gives a rapid, fairly accurate estimate of the composition of a natural glass. There are a number of rocks, such as ash, tuffs, etc., which cannot be cut into thin sections. In these cases, the index of the powdered glass can be obtained with special facility, and this is about the only method of study, except the more difficult chemical analysis.

The fact that balsam has an index of refraction of 1.537 ± 4 extends the range of application to thin sections. By referring to the index of refraction of glasses in several families, it will be seen that rhyolite, trachite, dacite, and andesite glasses have, as far as is known, an index of refraction less than 1.54. The rare leucite tephrite glass may have indices less than 1.54, but the average for this glass is 1.55. The basalt glasses have indices well above 1.54. Nine of the eleven specimens of basalt glass determined by the

[1] Judd and Cole, *op. cit.*, p. 451.

[2] *Ibid.*, p. 461.

[3] Penck, *Zeitschr. d. deut. Geol. Gesellsch.*, Vol. XXXI (1879), pp. 531 f.

[4] *Op. cit.*, p. 445.

writer were above 1.56, and the two exceptions were probably erroneously labeled.

Some isotropic minerals, such as analcite, have been confused with natural glasses.[1] Analcite has an index of refraction of 1.487 and a specific gravity of 2.25±, and occurs in relatively basic rocks. If a groundmass is discovered in a partly crystalline basic rock and the index of refraction (or gravity) is low, it should be taken as a strong indication that the ground mass is not glass, but rather, analcite.

"Ramosite" was first described as a mineral and later as a glass.[2] Ramosite, however, has a hardness of 8 to 9 and a specific gravity of 3.83. In both these points the original description of ramosite disagrees notably with published descriptions of glass and with all glasses in our collection.

CONCLUSIONS

The range of composition in natural glasses is practically that of the common crystalline rocks including a few alkalic types, but none of the extreme differentiates. The index of refraction and the specific gravity are closely related to the composition. Classification may usually be made most easily by determining the index of refraction, but the specific gravity may give additional information. Fusibility, color, hardness, solubility, and magnetism are found to be unreliable indications of the nature of the glass, though suggestive in many cases.

The importance of the distinction in crystalline rocks between alkalic and subalkalic rocks led to a special attempt to correlate the amount of alkali with some physical properties. The data are not very complete, but it seems that alkalic glasses show a higher index of refraction than subalkalic rocks of the same density. A determination of both specific gravity and index of refraction give about all the data on composition that can be expected without actual analysis.

[1] Attention was called to this by L. V. Pirsson, "Analcite Group of Igneous Rocks," *Jour. Geol.*, Vol. IV (1896), p. 683; N. W. Perry, *Trans. Amer. Inst. Min. Engrs.*, Vol. XII, pp. 628–29; Lee McA. Luquer, *Amer. Jour. Sci.*, Fourth Series, Vol. XVII (1904), p. 94.

[2] Lee McA. Luquer, *loc. cit.*

Acknowledgments.—The work on this paper was started by Martin Van der Linden, who was a graduate student in the department of geology in the University of Minnesota, and whose sudden death in January, 1920, brought an end to his investigations. The specimens he obtained by correspondence with several institutions form a part of those studied by the writer.

To Henry S. Washington, of the Geophysical Laboratory, Carnegie Institution of Washington, the writer is especially indebted for a number of specimens and his interest in the work. To others who have contributed a number of specimens, the writer wishes to express his thanks. Dr. Frank F. Grout, of the University of Minnesota, proposed the subject and suggested the possible results of its study.

THE TEMPERATURES OF HOT SPRINGS AND THE SOURCES OF THEIR HEAT AND WATER SUPPLY. III[1]

THERMAL SPRINGS OF THE SOUTHEAST ATLANTIC STATES

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INTRODUCTION

Thermal springs occur in Virginia, North Carolina, and Georgia, among the southeast Atlantic group of states. They belong to the group of low-temperature thermal waters. The temperatures range from slightly above the annual mean temperature to a maximum of 106° F. (41.1° C.) for the Spout Spring at Hot Springs, Virginia. Most of the springs are important health and pleasure resorts, and the waters are widely known for their medicinal value. Excepting the thermal waters of the Warm Spring Valley, Virginia, temperature and discharge data are lacking upon which to base a definite statement as to whether they are constant or variable, although statements have been made that both temperature and discharge are constant.

Of the more than a score of thermal springs listed by Rogers in Virginia, for which temperature data are given, only those of the Warm Spring Valley are included here, since the temperature of most of the others is only a few degrees above the atmospheric mean. Only four thermal springs are known south of Virginia: one in North Carolina and three in Georgia. The temperature data are given under the individual states.

The thermal springs of the region are distributed over three distinct physiographic provinces, each of which shows marked differences in geology. Those of Virginia occur in the Appalachian Ridges subprovince of the Appalachian Valley; of North Carolina, in the

[1] Continued from *Journal of Geology*, XXXII, 310.

Great Smoky Mountains of the Appalachian Mountains province; and of Georgia, in the Piedmont Uplands province.

The object of the present study is to summarize the authentic data relating to the thermal springs of the foregoing region and to point out, so far as may be warranted from existing knowledge, the probable source of the waters and their temperature.

PREVIOUS PUBLICATIONS

Most of the publications on the thermal waters of the region are limited to brief statements of analyses and temperatures of the waters, and of their medicinal value. Accurate discharge data have not been recorded. The publications by Rogers[1] and Weed[2] are the only ones which discuss the relations of the waters to the geology.

All the areas are covered by topographic maps prepared by the U.S. Geological Survey, and the Georgia area is the only one not mapped geologically.[3]

CHEMICAL ANALYSES

Analyses of the thermal waters tabulated below were all reduced to the normal standard. They represent waters of the mixed type containing carbonates, sulphates, and chlorides all together—a type which is very common. The predominant salts contained in them are carbonates and sulphates of the alkaline earths, calcium and magnesium, with small amounts of sulphates and chlorides of the alkalies, sodium and potassium. The waters of the Warm Spring Valley, Virginia, emit large amounts of gases, the character of which is shown in the analyses given in Table III. The composition of the waters represented by the analyses given in Table I is more

[1] William B. Rogers, "On the Connection of Thermal Springs in Virginia, with Anticlinal Axes and Faults," *Trans. Assoc. of American Geologists and Naturalists*, 1840–42. *Geology of the Virginias*, pp. 578–97. A reprint of annual reports and other papers. New York: D. Appleton & Co., 1884. "Analyses of Waters of the Principal Mineral Springs of Virginia," *ibid.*, pp. 547–64. "Temperatures of the Warm, Hot, and Sweet Springs, as observed by J. A. Chevallie, Esq., in 1806, and by myself and Dr. J. B. Rogers in 1834 and 1838," *ibid.*, pp. 565–66.

[2] W. H. Weed, "Notes on Certain Hot Springs in the Southern United States," *U.S. Geol. Survey Water-Supply and Irrigation Paper 145*, pp. 185–206, 1905, especially pp. 185–89 for Georgia, North Carolina, and Virginia.

[3] N. H. Darton, "Virginia-West Virginia," *U.S. Geol. Survey, Monterey Folio 61*, 1899; A. Keith, "North Carolina-Tennessee," *U.S. Geol. Survey, Asheville Folio 116*, 1904.

TABLE I

ANALYSES OF THERMAL WATERS OF VIRGINIA, NORTH CAROLINA, AND GEORGIA*

	I	II	III	IV	V	VI	VII
Cl	0.64	1.05	1.24	2.21	3.24	4.41	9.62
SO_4	21.73	38.38	20.70	48.51	13.17	4.59	1.04
CO_3	40.02	22.71	40.18	15.99	34.50	44.83	40.67
Na	1.81	1.82	3.35	1.00	3.01	6.44	5.42
K	2.04	1.36	2.23	2.45	.29	2.66	2.64
Ca	23.35	21.78	22.59	18.94	12.51	14.55	21.05
Mg	5.82	5.00	5.57	3.36	8.58	6.03	3.21
Fe_2O_3	.....	.64	.06	.11	.82	.32	.62
Al_2O_3	.58	.16	.12	.09	.82	.71	1.03
SiO_2	4.01	5.14	3.73	7.34	23.06	15.46	14.70
Li	.....	.04	.02	.....	.....	.....	.....
Sr	.....	.03	.15	.....	.....	.....	.....
Ba	.....	.01	.01	.....	.....	.....	.....
Mn	.....	.....	.02	.....	.....	.....	.....
Br	Trace	.....	.01	.....	.....	.....	.....
I	.....	Trace	Trace	.....	.....	.....	.....
F	.....	.01	.....	.....	.....	.....	.....
SO_3	.....	.96	.....	.....	.....	.....	.....
S_2O_3	.....	.91	.....	.....	.....	.....	.....
HPO_4	.....	.....	.02	.....	.....	.....	.....
	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Salinity parts per million.	563	530.3	628.4	735	123.5	138.8	81.7

* The writer is indebted to Professor F. P. Dunnington, University of Virginia, for recasting the analyses in this table, excepting I.

I. The Virginia Hot Springs, Bath County, Virginia. Average of six springs, analyzed by F. W. Clarke, *U.S. Geol. Survey Bull. 9*, p. 33, 1884. See *U.S. Geol. Survey Bull. 695*, p. 188, 1920. Traces of bromine were found in two of the waters; the other four were so similar to these that bromine was not specially sought for in them.

II. The Warm Sulphur Springs, Bath County, Virginia. Analysis by Henry Froehling. Folder published by the Virginia Hot Springs Company.

III. The Healing Springs, Bath County, Virginia. Analysis by Froehling and Robertson. Folder published by the Virginia Hot Springs Company.

IV. The North Carolina Hot Springs, Madison County, North Carolina. Analysis by C. F. Chandler and C. E. Pellew. Folder published by the Great Smoky Mountain Club, p. 11.

V. Warm Springs, Meriwether County, Georgia. Analysis by Edgar F. Everhart, *Geol. Survey of Georgia, Bull. 20*, p. 167, 1913.

VI. Lifsey Spring, Pike County, Georgia. Analysis by Edgar F. Everhart, *Geol. Survey of Georgia, Bull. 20*, p. 103, 1913.

VII. Thundering Spring, Upson County, Georgia. Analysis by Edgar F. Everhart, *Geol. Survey of Georgia, Bull. 20*, p. 157, 1913.

characteristic of meteoric (vadose) than of juvenile (magmatic) waters.

As shown in analyses V, VI, and VII (p. 375), the Georgia springs contain more SiO_2 and Cl and less SO_4 than those of Virginia and North Carolina. They may be classed as calcium carbonate waters with more chlorides and less sulphates than the thermal waters of the Virginia and North Carolina areas.

VIRGINIA THERMAL SPRINGS

The thermal springs of Virginia are the best known and have been the longest studied in the southeast Atlantic states. The contributions by Professor William Barton Rogers on these are the most important. Although Professor Rogers listed more than a score of thermal springs in Virginia, including several in West Virginia, giving temperature and other data on each, the thermal springs of the Warm Spring Valley, including the Hot, Warm, and Healing Springs in Bath County, have the highest temperatures and are the best known. The temperature of most of the others is only a few degrees above the annual atmospheric mean.

All the Virginia thermal springs are located in the folded Appalachians west of the Blue Ridge. The waters issue through Paleozoic sedimentary rocks, all of which have been strongly folded and in places profoundly faulted. Igneous rocks,[1] both acidic and basic, cut the Paleozoic sedimentary rocks in places, chiefly as dikes. They occur some distance from the springs, are not later than Triassic in age, are entirely cold, and have no relation to the thermal waters.

The linear grouping of the springs has long been recognized, and Professor Rogers early showed that the more decided thermal springs issue along or near lines of anticlinal axes. They are regarded as due to fractures or zones of crushing which may not always be visible at the surface. Those of the Warm Spring Valley rise along the west limb of the fold through steeply dipping nearly vertical beds of Cambro-Ordovician limestones (Fig. 1).

[1] Thomas L. Watson and J. H. Cline, *Bull. Geol. Soc. America*, Vol. XXIV (1913), pp. 301–34. N. H. Darton, *Amer. Jour. Sci.*, Vol. XXXIX (1890), pp. 269–71; *ibid.*, Vol. VI (1898), pp. 305–15. "Virginia–West Virginia," *U.S. Geol. Survey, Monterey Folio 61*, 1899.

FIG. 1.—Structure sections along a northwest-southeast direction through Warm Spring Valley, Bath County, Virginia. Section A is north of, but near, Warm Springs and about 3½ miles north of Section B which is north of, but near, Hot Springs. (N. H. Darton, *U.S. Geol. Survey, Monterey Folio 61*, 1899.)

Warm Spring Valley has resulted from deep erosion of the crest of Warm Springs Mountain, a conspicuous anticline of the Appalachian type, composed of Silurian sandstones or quartzites and shales overlying Cambro-Ordovician limestones. Steep dips, nearly vertical in places, characterize the west limb. Structure sections (Fig. 1) through Warm Spring Valley near the Hot and Warm Springs generalize the structural relations of the rocks.

The sections, adopted from Darton,[1] show the regular succession of formations and the absence of faulting, although faults may and probably do occur. The waters rise to the surface along fracture or slip planes in the limestone.

Temperatures.—Through the courtesy of the Virginia Hot Springs Company, the writer, assisted by Mr. C. M. Nevin, measured the temperature of the waters of the Hot Springs, Warm

TABLE II

TEMPERATURES OF VIRGINIA SPRINGS

	Temperature °F.	Radioactivity Mache Units*
Hot Springs:		
Spout Spring	105.8	16.551
Boiler Spring	104.9	86.54
Octagon Spring	98.6	4.889
Hot Sulphur Spring	98.6	101.87
Magnesian Spring	95.9	260.95
Warm Springs:		
Drinking Spring	95.5	.....
Gentlemen's Pool	95.9	95.72
Ladies' Pool	95	.....
Healing Springs:		
Bottling Spring	86	.....
Drinking Spring	83.3	69.621
Large Spring Feeding Bath	81.5	.....

* Drs. John C. Hemmeter and Ernest Zueblin, Baltimore, Maryland.

Springs, and Healing Springs of the Warm Spring Valley, July 17, 1923, with the results tabulated in Table II. The thermometers used by the writer were standard instruments loaned by Mr. C. E. Van Orstrand of the U.S. Geological Survey. The results are considered as accurate, since two thermometers were used in every test and the readings were identical in each case.

[1] N. H. Darton, "Virginia-West Virginia," *U.S. Geol. Survey, Monterey Folio 61*, 1899.

In 1806, J. A. Chevallie[1] recorded temperatures of 108° F. for the Spout Spring at Hot Springs, and of 96° F. for the Warm Springs. In 1834–38, William B. Rogers and J. B. Rogers[2] gave the temperatures of the same springs as 108.5° F. and 96° F.

Considering the greater accuracy of the present-day standard thermometers and the physical improvements made at the springs since the earlier observations, the temperatures recorded by Chevallie and the Rogers brothers and those by the writer 117 years later are remarkably concordant. The observations which cover a period of more than 100 years further show that the temperature of the different springs is essentially constant.

Radioactivity.—The radioactivity of the waters of the springs was recently tested by Drs. Hemmeter and Zueblin[3] with the results given in Table II. The tests show a range from very weak to strong radioactive waters, but the authors concluded that no relationship existed between the temperature and radioactivity of the waters. This conclusion is confirmed by tests made of some of the adjacent cold springs waters which yielded results (up to 92.63 Mache units) much higher than some of the thermal springs waters.

Composition.—The general chemical character of the waters is indicated in the analyses given in the table on page 375. The gases dissolved in the water consist of carbon dioxide, hydrogen sulphide, nitrogen, and oxygen. At some of the springs there is a decided odor of hydrogen sulphide gas, and in places a slight amount of separated sulphur formed from oxidation of hydrogen sulphide is noted on the bottom of the springs. The gases emitted by these waters were analyzed by Dr. Henry Froehling, with the results given in Table III.

NORTH CAROLINA THERMAL SPRINGS

Hot Springs, Madison County, represent the only thermal waters known in North Carolina. They are located on French Broad

[1] William B. Rogers, *Geology of the Virginias*, p. 565.

[2] *Ibid.*

[3] John C. Hemmeter and Ernest Zueblin, *The Radioactivity of the Mineral Waters of Hot Springs, Warm Springs, and Healing Springs in Hot Springs, Virginia.* Baltimore, Maryland, 16 pp.

River in the Great Smoky Mountains, the geology of which has been mapped and described by Keith.[1]

A great curved fault passes just north of Hot Springs which, according to Keith, has a displacement of at least 3 miles. Its trace at the surface forms a nearly complete oval and "its plane dips successively toward all points of the compass." The fault involves, besides, igneous rocks of pre-Cambrian age, quartzites and slates of Cambrian age. The igneous rocks include chiefly granites and gneisses and some basic rocks. The structural relations of the rocks are generalized in Figure 2, structure sections drawn along lines approximately at right angles to and across the fault trace.

TABLE III

ANALYSES OF GASES IN THE VIRGINIA THERMAL SPRINGS

	CO_2 (Per Cent)	N (Per Cent)	H_2S (Per Cent)	O (Per Cent)
Hot Sulphur Springs	11.25	83.75	0.75	4.25
Magnesia Spring	10.25	89.75	Tr.	Tr.
Boiler Spring	9.1	90.8	0.10	None
Octagon Spring	10.30	89.70	Tr.	.....
Healing Springs	9.75	90.25	None	None
Warm Sulphur Springs	4.03*	.....	0.19*	.....

* Cubic inches.

The water of the springs has a temperature of 104° F. and rises to the surface near the trace of a major thrust fault having a throw at this position, according to Weed,[2] of about 6,000 feet.

GEORGIA THERMAL SPRINGS

Warm Springs, Meriwether County, Thundering Spring, Pike County, and Lifsey or Pine Mountain Spring, Upson County, are the only thermal springs known in Georgia. The three springs are located in the Piedmont Uplands. They issue at the surface along the northwest of base of Pine Mountain, a low but conspicuous ridge composed chiefly of quartzite and quartz schist. Pine Mountain is nearly 70 miles long in a general northeast-southwest direction and rises to an elevation of several hundred feet above the adjacent surface of the Piedmont Upland.

[1] *Loc. cit.*

[2] W. H. Weed, *op. cit.*, p. 186.

FIG. 2.—Structure sections along a N. 13° E. direction through and west of Hot Springs, Madison County, North Carolina. Section A is through Hot Springs; Section B is about 1 mile west of Section A. (A. Keith, *U.S. Geol. Survey, Asheville Folio 116*, 1904.)

The region is unmapped, hence the geologic relations are not accurately known. The rocks of the Piedmont Upland are chiefly micaceous schists and gneisses whose foliation has a general northeast-southwest strike and steep but variable dips. They are probably pre-Cambrian in age, while the quartzite of Pine Mountain may possibly be Lower Cambrian. A short distance to the north of the springs the writer[1] has shown the rocks to be cut by massive biotite granite of probable early Paleozoic age. Dikes of diabase, Triassic in age, occur in places and are the youngest igneous rocks known in the state. Neither the granite nor the diabase is related to the springs waters.

Weed[2] finds distinct evidence of faulting at Warm Springs and states that the hot waters issue "from along a fracture at the base of a north shoot or spur of the main mountain mass." Probably similar relations obtain farther northeast along the base of Pine Mountain at Thundering and Lifsey Springs.

Analyses of the waters from the three springs are given in the table of analyses on page 375. Analyses by Everhart[3] of cold water springs occurring near the thermal springs are quite similar for the two classes of waters, except that the thermal waters contain a larger amount of dissolved mineral matter. McCallie[4] gives the temperature of the springs as follows: Warm Springs, 87° F., Thundering Springs, 76° F., and Lifsey Spring, 77° F. The discharge of Warm Springs has been determined by the U.S. Geological Survey to be 1,892 gallons per minute. Temperature and composition of the waters of the Georgia thermal springs and their geologic relations point to a meteoric source.

SOURCE OF THE WATERS AND OF THEIR TEMPERATURE

Geologically the thermal springs of the region occur in areas of disturbed rocks removed some distance from visible igneous masses which range in age from pre-Cambrian to Triassic, and from metalliferous vein deposits. The waters issue at the surface along fractures or faults, zones of crushing, and parting planes and apparently

[1] Thomas L. Watson, *Geol. Survey of Georgia, Bull. 9-A*, 1904.

[2] W. H. Weed, *op. cit.*, p. 187.

[3] S. W. McCallie, *Geol. Survey of Georgia, Bull. 20*, 190 pp., 1920.

[4] *Ibid.*

are not connected either with igneous rocks or metallic vein deposits. They belong to the fissure type of springs.

The waters, composed of a mixture of carbonates, sulphates, and chlorides, represent a common type which is regarded as more characteristic of a meteoric than of a magmatic source. The nature of the dissolved gases in the waters accords with this statement. Available analyses of nearby cold springs waters indicate compositions similar to those of the thermal springs. Except for higher temperature and the amount of gases contained in them, the thermal waters are similar to those of the cold springs in the individual areas.

Data on the Warm Spring Valley, Virginia, thermal waters indicate constant temperature for the individual springs. Accurate discharge data, however, are lacking, but opinion is current that the flow is also constant. Similarly there is lack of authentic analyses over a sufficient period of years upon which to draw conclusions as to the constancy or variableness of the amount of dissolved salts in the waters of individual springs.

The several observers who have given most attention to the thermal springs of the region not only affirm the meteoric source of the waters, but that their temperatures are due to the downward increase of temperature with depth. Available data seem to support the conclusion that the source of the water is chiefly, if not entirely, meteoric, but are possibly less conclusive as to the source of the heat.

Tests made of the Virginia waters indicate that radioactivity shows no parallelism with the temperatures, which is in accord with data on thermal springs of other regions studied. Similarly it seems doubtful from the analyses of the waters whether chemical reactions can account for much, if any, of the heat, although the temperature of the waters is low.

As pointed out above, igneous rocks are exposed at the surface in each of the thermal springs areas, but they are in less volume and farther removed from the springs in Virginia than in North Carolina and Georgia. While igneous rocks younger than Triassic in age are unknown in either area, a possible source of heat in buried uncooled rock masses cannot now be eliminated. Indeed evidence

for such source of heat is not entirely lacking in the case of the Virginia thermal waters.

Although the rate of temperature increase with depth is unknown for any of the thermal springs areas, if we assume a temperature increment of 1° F. for each 60 feet of depth and the known mean annual temperature of 50.6° F. as determined by the United States Weather Bureau, most of the heat might be derived from a depth of less than 3,500 feet in case of the hottest waters of the region (Hot Springs, Virginia). The writer is aware that objections, a discussion of which is beyond the scope of this paper, might be urged against increase of temperature with depth as a source of temperature, even though the estimated depth be moderate. However, what the probabilities are from other possible physical sources of heat as controlling factors must await more detailed geologic observations in the different areas.

THE HOT SPRINGS OF THE REPUBLIC OF HAITI[1]

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The Republic of Haiti (see map, Fig. 1) contains a number of warm springs of considerable interest. These are commonly known by the generic name of *sources chaudes* (warm springs), local geographical names being added to distinguish them from one another. Four of these groups of springs will be described in order as numbered in Figure 1.

1. WARM SPRINGS OF TERRE-NEUVE, OR EAUX BOYNES

The Eaux Boynes, also known as the Sources Chaudes de Terre-Neuve or de Port-à-Piment, are the most celebrated warm springs of the republic. They have long enjoyed a reputation for having great curative properties, particularly for skin diseases and for rheumatism, and so have been much frequented by invalids.

[1] Published by permission of the acting director of the U.S. Geological Survey and the engineer-in-chief of the Republic of Haiti. Abstracted from *Geology of the Republic of Haiti*, by W. P. Woodring, J. S. Brown, and W. S. Burbank. Republic of Haiti Geological Survey. (In press.)

Moreau de St. Méry[1] describes them at length, and tells of their utilization by the French colonists. The springs, and their curative value as well, are said to have been discovered by a negro named Capois in 1725. They soon became a noted rendezvous of health-seekers. In 1772 M. de Raméru, owner of the springs, gave them to the Crown in order that they might be used entirely for the public good. The government erected a military hospital at the

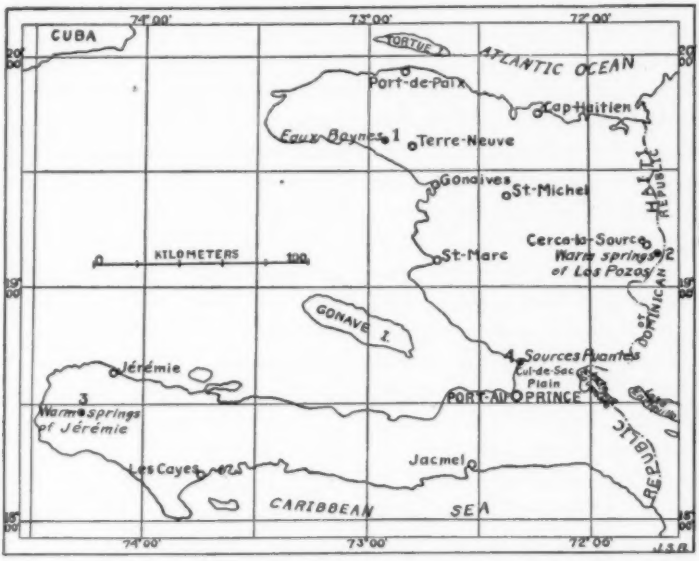

FIG. 1.—Index map showing location of warm springs in the Republic of Haiti.

place, and also a sanitarium open to the public at reasonable rates. There were sixteen masonry baths for the public besides those for the soldiery. Beautiful avenues of trees adorned the place. A passenger boat made bimonthly trips between Cap-Haitien, the Colonial capital, and the landing at Port-à-Piment.

All this contrasts strangely with the present dilapidated condition of the place. Only the ruins of eight of the masonry baths

[1] L. E. Moreau de St. Méry, *Description topographique, physique, civile, politique et historique de la partie Française de l'isle Saint Domingue.* 2 vols. Philadelphia, 1797–98. See Vol. II, pp. 62–75.

remain. There is no trace of the fine buildings, and the avenues of trees are gone. Nevertheless, the springs still make a green and pleasant oasis in what is virtually a desert, and nourish a vicarious planting of cocoanut trees and several thickets of bayahonde. There is a small agricultural settlement, with a few simple, thatched houses, whose inhabitants pasture their animals in the region and irrigate some diminutive gardens near the springs. In spite of the lack of accommodations many persons still visit the springs to test their healing power.

The Eaux Boynes are about 12 kilometers west of Terre-Neuve and 30 kilometers northwest of Gonaives. They are about 8 kilometers from the sea, at the inner edge of a narrow coastal plain. Behind them to the north and east is a narrow belt of low foothills and beyond that a range of mountains which rises abruptly to an altitude of more than 1,000 meters above sea level. The springs themselves are less than 100 meters above sea level.

The relation of the springs to the surface features in the locality is shown[1] in Figure 2.

It is said that formerly there were seven springs, but now only six can be found. It is probable that the other was developed by trenching in a marshy spot, and has since been obscured by débris. Of the six existing springs, five have a remarkably perfect alignment in a direction about N. 55 W. The springs at the ends of this line are about 235 meters apart. The sixth spring is offset considerably to the south of the easternmost spring. Some details regarding each outlet are given in the following paragraphs.

Grossier Spring is on a distinct mound that is situated on the bank of a small dry ravine about 3 meters in depth. The mound is formed of black soil full of humus, and is covered by a thick tangle of trees, chiefly bayahonde (a relative of the mesquite). Water issues mainly from an outlet on the west side of the mound, away from the ravine, but a little also issues on the side nearest the ravine. The flow does not exceed 2 or 3 gallons per minute. The temperature in the little pool at the larger outlet is 49° C. (120° F.) The water is not used.

[1] Part of the illustrations in this report were made up to accompany a French edition and are in French.

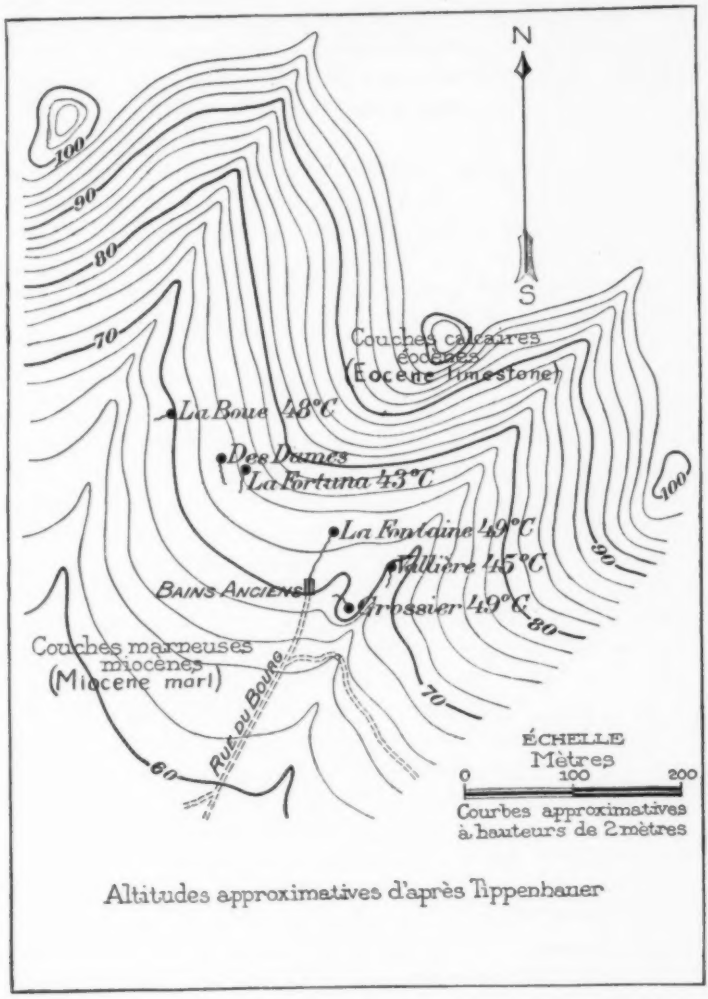

FIG. 2.—Sketch map of the Eaux Boynes, or Warm Springs of Terre-Neuve. (From *Geology of the Republic of Haiti.*)

Vallière Spring is in the bed of a shallow ravine, and issues from a little basin in black soil. It yields perhaps 5 gallons per minute of water with a temperature of 45° C. It is used little or not at all.

La Fontaine rises from a bowl-shaped basin about ½ meter in diameter in black soil. It has the largest flow of any spring of the group, estimated at 10 to 15 gallons per minute. The temperature in the outlet is 49° C. Bubbles of gas rise very slowly, at intervals of several seconds. There is little or no odor, and careful test showed only a trace of H_2S. The gas probably is CO_2. From the spring the water is led through a canal for 50 or 60 meters to the ruins of the eight masonry baths, and to a fountain and watering trough. Virtually all the water for domestic use and for drinking in the village is carried from this fountain. The water is clear and has a faint, peculiar taste, but is neither unpleasant nor harmful, even when taken warm. An analysis of water from this spring is given in Table I.

La Fortuna and Des Dames springs are covered and issue through short aqueducts. They are used for laundry work and for irrigation. The flow of each spring is less than that of La Fontaine. No temperature reading could be obtained near the outlet of Des Dames, and that at La Fortuna, 43° C., was taken in seep at one side of the broken cover and probably is too low.

La Boue Spring issues from a very small basin in black earth, and flows into a large dirty pool several meters in diameter. Its flow is not more than 4 or 5 gallons per minute, with a temperature of 48° C. Bubbles of gas rise at intervals as at La Fontaine. No particular use is made of the spring.

The line of springs is plainly situated at the break in slope from foothills to plain, but cuts across a low ridge between two ravines, ignoring the minor details of the topography. Geologically the springs appear to occupy a well-defined contact, although only alluvium and residual soil are visible around their outlets. Soft, marly beds of Miocene age, which are exposed less than a kilometer to the south, presumably underlie the whole coastal plain. The foothills, on the other hand, consist of limestone, presumably the lower part of the thick Upper Eocene limestone which covers extensive areas in the mountains to the east and north. This rock is

exposed on a hill about 200 meters northeast of the springs. It is a hard, yellowish-white limestone, poorly exposed, and with indeterminable bedding. The Miocene beds, generally, dip seaward at low angles; the Eocene rocks probably also dip seaward, judging from their relations elsewhere.

The position of the springs at a topographic break and near a geologic contact, and their alignment parallel to the major structural trends of the region, suggest strongly that they issue along a fault zone, and the temperature of the water indicates that it must rise from considerable depth. Further discussion of their origin follows the description of the other groups of warm springs.

2. WARM SPRINGS OF LOS POZOS

This description is based upon information supplied by W. P. Woodring. The warm springs of Los Pozos are on the estate of Charles Zamor, in the section of Los Pozos, about 6 kilometers southeast of Cerca-la-Source. They are reported to have therapeutic value, especially in the treatment of skin diseases, but are not much used for any purpose. At two of the five springs there are crude shelters for bathers, but there is no settlement at the springs.

The springs are at the southern border of the valley of Rivière l'Océan and at the foot of a rounded escarpment in Upper Oligocene limestone. Farther northwest, near Cerca-la-Source, this escarpment becomes high and precipitous. There are five springs, four of which are arranged along a straight line trending about N. 70° W., on the northeast side of the trail from Cerca-la-Source to Los Pozos. The local geography is shown in Figure 3. Notes on the separate springs, whose names were not ascertained, follow. None of the springs flows more than a few gallons per minute.

1. Water seeps out along the trail and is conducted about 5 meters down the slope to a wooden tub, hollowed out from a log. Over the tub is a crude shelter. This water had a temperature of 36° C.

2. This is a small seep, not cleaned out. The temperature was 38° C.

3. This is the largest spring of the group, and also has the highest temperature (42° C. = 108° F.). The water issues from an opening

between two large limestone bowlders that have come down the slope. It has a strong odor of hydrogen sulphide (H_2S). Algae grow abundantly in the spring. Over it is a crude shelter. An analysis of a sample of water from this spring is given in Table I. Unfortunately no means were available to fix the hydrogen sulphide (H_2S), which otherwise evaporates quickly, so that this constituent was not determined.

FIG. 3.—Sketch map of the warm springs of Los Pozos. (From *Geology of the Republic of Haiti.*)

4. This is a small spring, and not cleaned out. The temperature of the water was 31.5° C.

5. A trench has been dug in the slope to increase the flow of this spring. The opening is lined with rough limestone blocks. The temperature was 40° C.

As previously stated, the escarpment southwest of the springs is of Upper Oligocene limestone. The valley to the northeast is underlain by semi-metamorphosed shales, supposedly of Middle or Lower Cretaceous age. A fault is believed to exist along the

base of the limestone escarpment. Certainly it seems reasonable to assume that the springs issue along a fault zone, since they are aligned parallel to the contact of the formations and to the strike of the rocks, as well as to the prevailing structural trends. The source of the water will be considered later.

3. WARM SPRINGS OF THE SOUTHERN PENINSULA

Several warm springs are known in the interior of the western part of the southern peninsula of Haiti. According to Moreau de St. Méry[1] and other writers, warm springs exist at four localities, three on the "Bras-Gauche" or eastern fork of the Grand River of Jérémie, and one on the "Bras-Droit" of the same stream. This latter group of springs is on the headwaters of the Bras-Droit almost in the bed of its deep, narrow valley, and is known as the warm springs of Les Irois or of Anse-d'Hainault. Two groups are near the headwaters of the Bras-Gauche, one group on a tributary ravine about 600 meters west of that stream, and the other group in the bed of the Bras-Gauche about 600 meters downstream from the junction of the ravine. These springs are known as the warm springs of La Cahouane or of Tiburon. According to Moreau de St. Méry, their temperatures were 34° C. and 37.5° C.[2] About two leagues downstream from these springs are the warm springs of Dame-Marie or of Jérémie, evidently the ones visited by the writer and described in the following pages.

All the springs are supposed to have medicinal virtues, and are frequented considerably by persons from this part of Haiti; but the region is so rough and inaccessible that it is very thinly inhabited, and is seldom visited by strangers.

Warm springs of Dame-Marie or of Jérémie.—These springs are on the Bras-Gauche, the eastern fork of the Grand River of Jérémie, about 15 kilometers by a very difficult horseback trail above its junction with the Bras-Droit. For part but not all of the way the trail follows the river, which it crosses many times. At the springs are about half-a-dozen thatch shelters used by the transient visitors, but no permanent habitations.

[1] *Op. cit.*, Vol. II, pp. 759–60.

[2] Converted from degrees Réaumur.

The river valley is incised directly across high mountain ranges, and is deep and narrow. At the springs, however, the adjacent mountains are lower than farther north, and probably rise only 500 or 600 meters above the river. The elevation of the springs, according to a rather unreliable aneroid barometer reading, is about 190 meters above sea level.

There are two springs about 50 meters apart on the southwest bank of the river. The one farthest southeast is about 4 meters and the other only about 1.5 meters above the river bed. The lower spring issues plainly from a small fracture an inch or two wide in dark basalt, which is the prevailing country rock. The other doubtless issues from a similar fracture, but its outlet is obscured by débris. The water bubbles up with considerable force at each spring, but no gas bubbles were noted, and only a faint odor. The taste of the water is not unpleasant. No thermometer was available, but the temperature of the water probably is between 35° and 40° C. One can hold the hand in either spring indefinitely, without discomfort, whereas a few seconds is the limit at Eaux Boynes (49° C.).

There are no bathing facilities, except a sort of earthen-walled, rock-floored basin scooped out at the lower spring, and a quaggy area of mud at the upper spring, which is a favorite place for mud baths.

An analysis of the water is given in Table I, and its origin further discussed in a later section.

4. SULPHUR SPRINGS: "SOURCES PUANTES"

A number of springs in the Republic contain notable amounts of hydrogen sulphide (H_2S). The distinctive and rather unpleasant odor of the gas is responsible for the name *sources puantes* (stinking springs) frequently applied to them. The most famous of the kind are the Sources Puantes at the northwest corner of the Cul-de-Sac Plain (Fig. 1). The odor of these springs can be detected for some hundreds of meters. Many persons believe the springs to have healing virtues. There is an open basin for bathing, but it seems to be used very little. No one lives near the springs.

The original outlet of the springs has been disturbed somewhat by the building of a railroad embankment and highway crossing.

At present the largest flows of water issue from two small basins at the lower side of the embankment. Some water appears to seep out over a large marshy area about 100 meters in diameter. The flow of the springs is large, but difficult to estimate. The two large openings alone must yield 500 gallons per minute or about 1 second-foot. Bubbles of gas rise almost continuously both at the larger openings and at spots on the adjacent marshy area. Presumably, most of it is hydrogen sulphide (H_2S). This was fixed in the form of cadmium sulphide (CdS) by adding cadmium chloride ($CdCl_2$) to the sample, analysis of which is given in Table I. The water is appreciably warm, its temperature in December being 32.7° C. The taste of the water is salty and nauseating, although its appearance is clear and inviting.

TABLE I

ANALYSES OF WATER FROM THE WARM SPRINGS OF HAITI*

(Analyzed by C. S. Howard. Data are Parts per Million)

	1 Eaux Boynes (La Fontaine)	2 Los Pozos (No. 3, Fig. 3)	3 Warm Springs of Jérémie	4 Sources Puantes
Total dissolved solids	403	1,214	515	12,684
Silica (SiO_2)	35	15	68	36
Iron (Fe)	0.30	0.13	0.07	0.08
Calcium (Ca)	51	118	26	397
Magnesium (Mg)	21	33	1.4	299
Sodium and Potassium (Na+K)	56	223	135	3,930
Bicarbonate radicle (HCO_3)	277	260	93	610
Sulphate radicle (SO_4)	68	62	117	872
Chloride radicle (Cl)	36	464	121	6,627
Nitrate radicle (NO_3)	Trace	Trace	0.42	Trace
Hydrogen sulphide (H_2S)	Trace	Odor noticeable	.....	136
Date of collection of sample	Aug. 1921†	March 14, 1921	Nov. 16, 1920	Dec. 6, 1920

* All samples analyzed in the Water Resources Laboratory of the U.S. Geological Survey.
† Original sample broken in transit. This sample collected by Père J. J. Joliveau, of Terre-Neuve.

The springs are virtually at sea level, and the marshy area becomes a mangrove swamp only about 50 meters from the main outlet of the springs, with open salt water only a little farther away. Behind them rise low foothills underlain by Miocene rocks, which near the springs are covered by alluvium and conglomeratic débris. Beyond the foothills are high mountains of the older (Oligocene and

Eocene) limestones. The springs thus occupy a very narrow extension of the Cul-de-Sac Plain—a broad, level plain whose surface formation is recent alluvium, but which is underlain, presumably at no great depth, by Miocene beds.

The structural conditions at the springs are quite obscure. They may possibly issue along some undetermined fault, as faults are known to exist on both sides of the Cul-de-Sac Plain and to have had some share in the formation of the structural trough it occupies. Or they may merely rise because of artesian pressure at this low border of the plain where the alluvial formations become more conglomeratic and more porous. The existence of several artesian springs and numerous flowing wells in the Plain to the south and east accords well with this possibility.

As is brought out more fully later, the writer believes these springs are due to the escape of mixed meteoric and connate sea water under artesian pressure. The hydrogen sulphide probably is generated by chemical reactions during the escape of the water.

SOURCE OF THE WARM SPRING WATERS

As with many, if not most, hot springs, the source of the water in the hot springs of Haiti is a matter of uncertainty. We have the usual possibilities: (1) meteoric water heated (*a*) by descending to considerable depth, (*b*) by coming in contact with hot bodies of intrusive igneous matter; or (2) magmatic or juvenile water given off by cooling igneous matter. Any degree of admixture of water from the two sources is also possible, of course.

On the assumption of a meteoric source the springs might be expected to exhibit seasonal fluctuations in volume, particularly since the rainfall in Haiti is concentrated very notably into two wet seasons each year. No such fluctuations have been reported, but no careful observations have ever been made of the spring flow. The general characteristics of the springs seem not to have changed materially since the days of the French Colony, a fact that may seem to favor uniformity of flow, especially since many cold springs, such as those which furnish the public water supplies of Port-au-Prince and Cap-Haitien and which clearly are fed by meteoric water, are characterized by very marked fluctuations in volume.

However, it is questionable whether the flow in waters, circulating as deep as these necessarily must, might not be equalized so as to be relatively independent of the seasonal rains.

The temperature of the spring waters, even if no allowance is made for cooling on the way to the surface, would in all cases require them to descend to considerable depth to attain their heat merely by virtue of the earth's thermal gradient. The mean annual temperatures at stations which doubtless correspond closely with those at three of the springs are fairly well known.[1] Assuming an average thermal gradient of 1° C. for each 35 meters of depth, a figure that seems to be conservative from any point of view, the data for determining the depth of circulation are given in Table II.

TABLE II

DEPTH OF CIRCULATION NECESSARY TO HEAT SPRING WATERS

	Spring		
	Eaux Boynes (La Fontaine)	Los Pozos Spring No. 3	Sources Puantes
Temperature of spring. Degrees C.	49	42	32.7
Place of comparison	Gonaives	St.-Michel	Port-au-Prince
Mean annual temperature. Degrees C.	27	25	27
Excess temperature of spring. Degrees C.	22	17	5.7
Approximate depth of circulation required to heat water, due to Earth's thermal gradient. Meters	880	600	200

Exact data for the warm springs of Jérémie are lacking, but their excess temperature probably is about 10° C., equivalent, under the assumed conditions, to a depth of circulation of about 350 meters. With all the springs this would require circulation considerably below sea level, especially with the Eaux Boynes, which would be about 800 meters below sea level.

Except for the Sources Puantes, where artesian conditions probably exist, there is no evident structure adequate to account for such a circulation, although the adequacy of obscure structures afforded by fault zones is perhaps possible in all the cases. For the Eaux Boynes there is a suggestion of artesian structure in the

[1] From bulletins of the Séminaire-Collège St. Martial, Port-au-Prince.

seaward dip of the Eocene and Miocene beds, although no impervious cover can be demonstrated to exist in the Eocene limestone, which must be the major factor in any such circulation. Moreover, it is doubtful whether the limestone has the requisite thickness, as the beds exposed near the springs are believed to be the lower part of the series, which rests unconformably on an igneous complex. A sufficient thickness of sedimentary beds may very well exist at Los Pozos. For the warm springs of Jérémie there is apparently no possibility except circulation through massive basaltic extrusives, which only occasionally show good flow lines.

The analyses of the waters are probably not conclusive, though all differ notably from the normal cold spring waters of the Republic. These latter commonly carry less than 300 parts per million of total solids, at least 90 per cent of which is calcium and magnesium carbonate, or bicarbonate with the calcium element preponderant. This results from the great prevalence of calcareous rocks over the country. In both the Eaux Boynes and the Los Pozos analyses calcium and magnesium bicarbonates are still preponderant, though in smaller proportion, and calcium still exceeds magnesium. This seems to suggest strongly that whatever the source of the water, most of this part of its mineral content is derived from the calcareous formations encountered in the latter part of its upward journey. In both these analyses, however, the sulphate and chloride of sodium and potassium are out of all proportion to that found in normal meteoric water, and in the warm springs of Jérémie they are quite the dominant feature. Except perhaps at the Eaux Boynes, these constituents cannot possibly be attributed to a mixture of sea water, either directly or in the connate condition, and there is no apparent source for them in the rocks through which they circulate near the surface. In none of these waters, however, are metals or heavy elements, supposed often to characterize magmatic waters, present in more than minute traces. The presence of undetermined gas, probably CO_2, in the Eaux Boynes and the springs of Jérémie, will generally be regarded as favoring a magmatic source.

On general geologic grounds the probability of a magmatic source for at least some of the springs is not unreasonable. The

West Indies were the scene of very extensive Tertiary volcanic activity continued in certain areas, as is well known, to Recent time, although there is no evidence of Quaternary activity in the Haitian Republic. In the Terre-Neuve Mountains, about 12 kilometers from the Eaux Boynes, small intrusions at least as late as Oligocene and probably of Miocene age are known. No other volcanic activity of as late a date is known near any of the other warm springs.

It seems suggestive also that in the general locality of the warm springs of Jérémie there appear to be several other groups of similar springs in an area where it is difficult to find adequate structural conditions for a meteoric source, even in a single case.

The Sources Puantes seem to present a problem considerably different from that of the other groups of springs. In the first place their excess temperature above the mean annual temperature of the locality is much less, and does not necessitate circulation to an unreasonable depth, especially since artesian conditions are known to exist on the Cul-de-Sac Plain near by, where there are numerous flowing wells, several of which are more than 150 meters in depth. The water of these wells also is warmer than the air, although measurements unfortunately are lacking. The wells are mostly several kilometers south or east of the springs, but there seems to be no good reason why flows might not be obtained at some places much nearer the springs, if wells were drilled. The artesian water comes either from Recent alluvial strata, or from the buried Miocene beds beneath. It is supplied mainly from the mountains to the south of the plain, as those to the north are semiarid. Since the chief streams enter on the south side and deposit most of their sediment there, the plain has a gentle northward slope almost to the border of the northern mountains.

Analyses of water from the flowing wells seem to indicate that near the sea they become more saline, due either to admixture of sea water, or much more likely of connate water, present in the strata beneath the plain. Coral reefs present at places on the borders of the plain prove that in Pleistocene time it was submerged, so that undrained connate water might be expected in the deeper beds, especially near the sea.

There can be little doubt that the extraordinary salinity of the Sources Puantes is due chiefly to admixture of sea water either directly or in connate form. The relation of the spring water to sea water is indicated in the following comparison:

TABLE III

COMPARISON OF THE COMPOSITION OF AVERAGE SEA WATER WITH THAT OF THE SOURCES PUANTES

(Percentage of Dissolved Solids)

	Sources Puantes	Sea Water
Cl	53.2	55.29
Na+K	31.5	31.70
SO_4	7.0	7.69
Ca	3.2	1.20
CO_3	2.4	0.21
Mg	2.4	3.72
Total	99.7	99.81

The percentages of chloride, of sodium and potassium, and of sulphate correspond quite closely, and together constitute a very preponderant amount of the total. The concentration of the Sources Puantes is about one-third that of sea water. The variations in calcium, magnesium, and carbonate are quite within the limits one might expect if two parts of meteoric ground water were mixed with one part sea water, and are in the direction to be expected, namely, increase of carbonate and calcium, with calcium becoming preponderant over magnesium.

The writer prefers to attribute the salinity to connate water rather than the direct admixture of sea water, because in extensive studies elsewhere he has found that sea water can scarcely penetrate clastic sediments in such large amount even very near the shore,[1] and because the presence of connate water is in harmony with the circumstances in the case.

The hydrogen sulphide probably is derived from the sulphate of the connate sea water by chemical reactions through the agency of organic matter known to be abundant in the superficial material about the outlet of the spring and probably present also to con-

[1] See John S. Brown, "Relation of Sea Water to Ground Water along Coasts," *Amer. Jour. Sci.* (5), Vol. IV (1922), pp. 274–94.

siderable depth in the lower beds. Clarke[1] says: "The sulphates of a water by accession of organic matter can be partly or entirely reduced to sulphides, and carbonic acid, acting upon the latter, may expel sulphuretted hydrogen and produce carbonates." Some support is lent to this hypothesis by the fact that the sulphate in the spring water is slightly less than one-third that of sea water, whereas the sodium and potassium and the chloride slightly exceed one-third, indicating possibly that some sulphate has been reduced.

The writer does not wish to imply that this same explanation necessarily accounts for the presence of hydrogen sulphide in other springs of the Island which he has not examined.

SUMMARY

The Republic of Haiti contains a number of notable warm springs, four groups of which are described in this paper. For the first three of these groups the evidence is not conclusive, but probably favors a magmatic source. The fourth group is believed to represent mixed meteoric ground water and connate sea water in which much hydrogen sulphide (H_2S) has been generated by chemical reactions.

[1] F. W. Clarke, *Data of Geochemistry* (4th ed.), *U.S. Geol. Survey Bull. 695* (1920), p. 204.

THE DETERMINATION OF $2V$ IN SECTIONS PERPENDICULAR TO AN OPTIC AXIS

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ABSTRACT

A method is put forward whereby the optic angle of a crystal may be found in a section perpendicular to an optic axis. Curves of darkness for two series of spheroconics are drawn and the medial lines are plotted. The axis of the isogyre in a crystal section is referred to these curves whereby the value of $2V$ may be obtained to within approximately four degrees.

Among the methods already developed for measuring the optic axial angle there is none satisfactory for the case where one of the melatopes lies at the center of the field. Wright[1] has given a series of curves but these define only one boundary of the isogyre and do not take into consideration the fact that under the conoscope it is a bar and not a line that is seen. The factors determining the width of this bar will be dealt with later, but it is evident that to apply such a method as this it is the medial line that has to be considered. This medial line is the mean of the two curves of darkness To obtain it, the following method based on Hilton's[2] work was employed.

On the surface of a sphere of a birefracting crystal, the curves of equal velocity form two series of spheroconics whose foci are the points of emergence of the optic axes. The isogyres are the loci of those points on the spheroconics whose normals are parallel to one of the principal vibration directions of the nicols. In order to locate these points the following construction was used.

Figure 1 is a stereographic projection of a crystal so placed that one melatope, O, is at the center of the field of view. The other melatope, A, is in the forty-five degree position and, in this

[1] F. E. Wright, *Methods of Petrographic-Microscopic Research*, p. 168.

[2] H. Hilton, "Ueber die dunklen Büschel von Dünnschliffen im convergenten Lichte," *Zeitschrift für Krystallographie*, XLII (1906–7), 277–78.

case, sixty-five degrees distant. The axes *OX* and *OY* are the vibration directions of the nicols.

A great circle is drawn parallel to *OX* and intersecting *OY* in *D*. The arc *DN* is made equal to the arc *OD*. A great circle is now drawn through *A* and *N*, cutting the circle through *D* at *R*. *R* is a point on a spheroconic whose foci are *O* and *A*. Since by construction the angle *ORD* is equal to the angle *NRD*, *RD* is the normal to this ellipse at the point *R*. *RD* is also parallel to one of the vibration directions of the nicols, consequently *R* is a point on the curve of darkness due to the series of ellipses round the acute bisectrix.

A similar construction applies for the location of points on the curve of darkness due to the series of ellipses round the obtuse bisectrix except that in this case the first circle is drawn parallel to *OY*. The point, *T*, so obtained is on an ellipse whose foci are *O* and *A'* and *TC* is the normal at *T*.

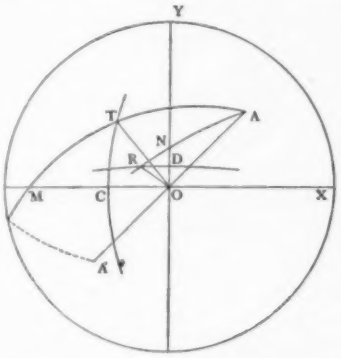

FIG. 1.—Construction used in locating the isogyres.

By carrying out this construction for axial angles between zero and ninety degrees two series of curves are obtained. These form a single set of diverging bars which represent the minimum divergence of the isogyre for any given angle. Figures 2, 3, and 4 give the curves at intervals of ten degrees for angles ranging from zero to ninety degrees.

The question now arises as to whether the curves seen under the conoscope represent the actual axial angle in the crystal. In Figure 6, *OR* and *OT* are the actual curves of darkness in the crystal. Consider the rays emerging at the points *R* and *T* on the circle *RT*. Due to refraction there will be a displacement of *R* and *T* along the radii *OR* and *OT*. This displacement will be the same in both cases. The resulting curve will diverge at a smaller angle if the refractive index is less than unity and may also be deflected. If the medial line of the original bar were much curved, then a

distinctly different direction would be given to the new curve. By referring to Figure 5, in which the medial lines are plotted, it is seen that the latter depart but slightly from straight lines in the

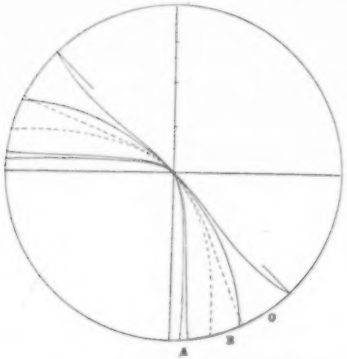

FIG. 2.—The isogyres for axial angles of 10° (A), 40° (B), and 70° (C).

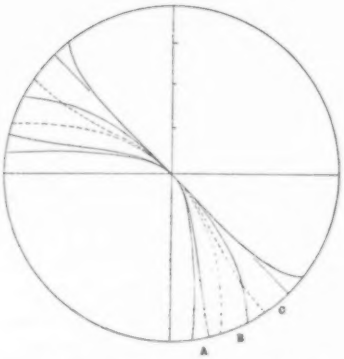

FIG. 3.—The isogyres for axial angles of 20° (A), 50° (B), and 80° (C).

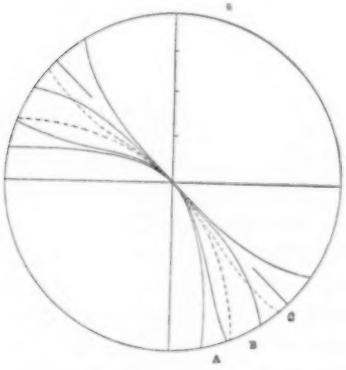

FIG. 4.—The isogyres for axial angles of 30° (A), 60° (B), and 90° (C).

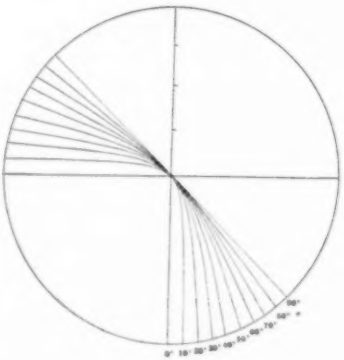

FIG. 5.—Curves obtained by drawing the medial lines of the isogyres in Figs. 2, 3, and 4.

outer part of the field. It is very improbable then that the refractive index will have any great effect on the direction of the medial line, especially near the edge of the field. This conclusion is

strengthened by the data from actual observation. It has long been known by petrographers that no matter what the refractive index of a mineral, if the real optic axial angle be ninety degrees the bar forms a straight line in the forty-five degree position.[1] In order to test further this relationship a section of topaz with an optic axial angle of sixty-seven degrees and one of aragonite with an optic axial angle of ten degrees were cut approximately perpendicular to the optic axes and compared with the curves deduced in

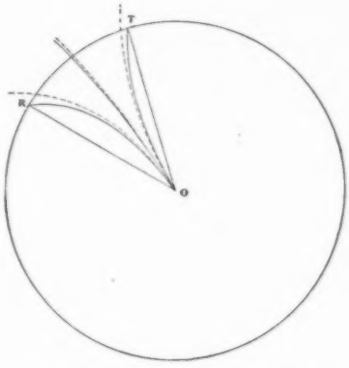

FIG. 6.—The dotted lines indicate the displacement of the isogyre due to the introduction of B.

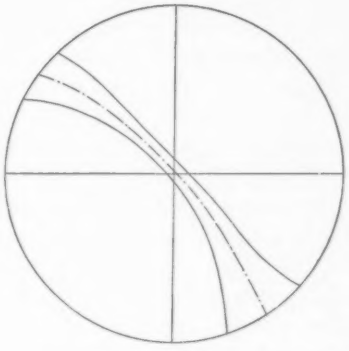

FIG. 7.—A camera-lucida drawing of the bar seen in a section of topaz, axial angle 67°, cut approximately perpendicular to an optic axis.

Figure 5. Figure 7 gives a camera lucida drawing of the topaz figure. It is slightly eccentric, yet the mean reading for the intersection of the medial curve with the circumference of the field is sixty-nine degrees. Allowing for the difficulty of locating exactly the limits of the bar, it appears that here again the curve is a function of the real optic axial angle. The aragonite crystal also showed a strict relation to $2V$.

From all these considerations it has been thought justifiable to take the curves of the medial lines as deduced in Figure 5 as a measure of the real optic axial angle.

[1] Albert Johannsen, *Manual of Petrographic Methods*, 1918, p. 424.

In order to apply this method some circle of reference must be given. This has been taken as the circumference of the microscope field. The angle subtended in the crystal by the diameter of the field varies with the refractive indices of different crystals. But the refractive indices of the minerals to which this method would be applied are all included in a range of from 1.5 to 1.8, that is, an average of 1.65 and most are close to the latter value. Topaz provides a very good standard. In almost all modern microscopes a basal section of the latter mineral gives the melatopes just outside the field. This means that the true angle subtended by the field is about seventy degrees. In order to give latitude in the use of the diagram, an eighty degree circle was drawn and the positions of sixty, forty, and twenty degrees marked.

In discussing the relation between the real angle in the crystal and the figure seen under the conoscope, reference may be made to a fallacy that has existed in the minds of some petrographers. It has often been suggested that in measuring the optic axial angle, by Mallard's constant for example, an immersion medium be used and the real angle read direct. A little consideration shows that the angle subtended in the crystal is quite independent of the refractive index of the medium. If a ray of light pass through three media whose refractive indices are n', n'', and n''' respectively, the angle of incidence at the first contact being i and the angle of refraction at the second contact r, then,

$$\frac{\sin i}{\sin r} = \frac{n'''}{n'}$$

That is, the angle measured by such a method is independent of the refractive index of the medium between the mineral and the objective. So far then as the microscope is concerned, the phrase "the angle in air" has no real meaning.

In plotting the above curves, orthographic projection was used. It was found that of all projections this was the one which gave the smallest divergence between the curves bounding the bar. The broadest was the gnomonic projection, then came the stereographic

and the angle meridian in order of decreasing width. In a mineral section the breadth of the bar seen depends on the thickness and, as has already been shown, on the refractive index. With a very thick section, the bar should approach the curves deduced, provided other factors do not interfere. It must be remembered, however, that as the thickness increases so also does the number of rings seen in the interference figure. These rings cause a decided prolongation of the bar beyond the limits set by the curves of darkness.[1] Since the bar is also thinner due to the refractive index it was thought better to draw the curves which gave the smallest divergence and so orthographic projection was employed.

The procedure used in the actual determination of optic angles is as follows. The cross-hairs are placed in the forty-five degree position and the section is rotated until one cross-hair is parallel to the bar at the melatope. The cross-hairs are then restored to the ninety-degree position. A camera lucida drawing is made of the isogyre and the medial line plotted. The intersection of the latter with the circumference is then referred to the chart and the value of $2V$ obtained. The method could be made direct reading by the use of on ocular containing a glass plate with the curves inscribed.

It very often happens that the section is not exactly perpendicular to an axis. If the eccentricity is slight it may be corrected by tilting the section, but so long as in the drawing the circles are described with the melatope as center, a small eccentricity introduces no very appreciable error.

The method is only accurate to within about four degrees. In this respect it is inferior to those of greater accuracy, but even with this drawback it is most serviceable, as the sections to which it is applicable can be readily recognized under crossed nicols.

The equations for the curves were deduced considering the construction carried out in three dimensions. The equation for the orthographic projection was also obtained. Of these equations the latter is much too unwieldy to be of any value as a check on the curves given in the diagrams. Since this *Journal* is not the place

[1] Albert Johannsen, *Manual of Petrographic Methods*, Fig. 589.

for a mathematical study, only the final equations of the three-dimensional solution are given below. They are:

$$\frac{z^2-y^2}{2yz}\left\{\frac{y_1}{x_1}x-y\right\}-\frac{z_1}{x_1}x+z=0$$

$$x^2+y^2+z^2=r^2$$

where $(x_1\ y_1\ z_1)$ are the co-ordinates of the other melatope and r is the radius of the sphere. When the line joining the melatopes is inclined at forty-five degrees to the principal directions in the nicols, $x_1=y_1$ in the foregoing. This is the case dealt with in the paper.

In conclusion the writer desires to express his indebtedness to Dr. Johannsen for his advice and criticism.

THE BREAKING OF WAVES IN SHALLOW WATER

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ABSTRACT

The energy of waves of oscillation entering shallow water is transferred to lesser and lesser numbers of water particles, causing them to revolve in larger and larger orbits. But the number of waves which pass a point in a given time is observed to remain constant. The water particles, therefore, must complete the circuit of their larger orbits in the same length of time that was occupied in describing their smaller ones, and so must acquire greater orbital velocity. Decrease of wave-length in shallow water retards the forward propagation of the wave. When the increasing orbital velocity of the upper water particles becomes greater than the forward motion of the wave, the wave breaks.

The widespread and venerable idea that waves break because friction from dragging bottom in shallow water so retards the lower part of the wave that the top pitches forward, has encountered formidable, indeed fatal objections. The friction would be too slight to produce so considerable an effect; and in fact experiments fail to show any appreciable frictional retardation.[1] An alternative explanation was presented by Hagen,[2] who recognized that the increasing height of waves entering shallowing water meant that the particles of water were traveling in larger orbits. As Johnson sums it up:

> With constantly enlarging orbits and diminishing water supply, there must come a time when the volume of water is insufficient to build up the entire wave form, the deficiency manifesting itself as a "hollowing" of the front of the wave. The water available endeavors to curve around through the entire orbit, but on reaching the top of the circle finds itself unsupported and collapses.[3]

The phrase "insufficient water to build up the wave form" is vague to some students for whom the mechanics of the problem need further discussion. The following explanation, based on two

[1] Otto Krümmel, *Handbuch der Ozeanographie*, Vol. II, p. 112. Stuttgart, 1911.

[2] G. Hagen, *Handbuch der Wasserbankunst*, 3 Teil, *Das Meer*, Vol. I, pp. 19, 86. Berlin, 1863.

[3] D. W. Johnson, *Shore Processes and Shoreline Development*, p. 16. New York, 1919.

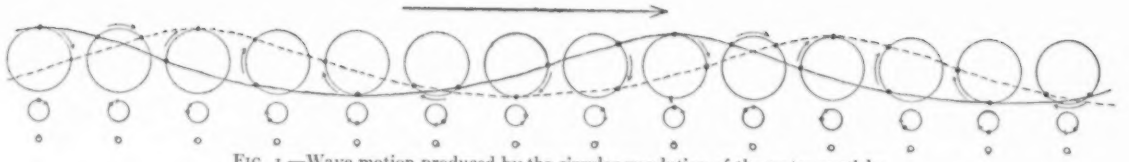

FIG. 1.—Wave motion produced by the circular revolution of the water particles

FIG. 2.—The crest of the wave form is made steeper and higher by greater amplitude of displacement of the water particles. In this diagram no forward motion of the wave is shown.

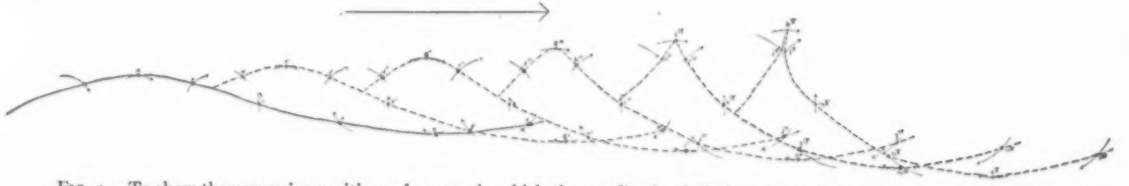

FIG. 3.—To show the successive positions of a wave in which the amplitude of displacement of the water particles becomes greater and greater while the wave-length becomes shorter and shorter. The original wave-length is 10 inches; the amplitude of displacement is $\frac{3}{16}$ inch. At each successive position of the wave the wave-length is shortened $\frac{5}{8}$ inch while the amplitude of displacement is increased $\frac{1}{8}$ inch.[1] The successive position of each water particle is shown, e.g., d, d', d'', etc.

[1] The length of wave and the amplitude of displacement are entirely arbitrary and were selected only for diagrammatic purpose. Likewise the shortening of the wave-length and the increase of amplitude are not measured or computed values, but were selected as convenient units to show on the diagram how the wave breaks. With an onshore wind, waves break in much deeper water than with an offshore wind. Other factors, such as the topography and slope of the bottom, also influence the depth at which waves of a given height break, to such an extent that mathematical consideration of the ratio of wave-shortening to increase of amplitude of the water particles is beyond the scope of this discussion.

of the simpler of the well-known physical laws of wave motion, is offered:

1. Waves of oscillation in deep water are the expression of simple harmonic motion resulting from the circular revolution of the water particles.[1] The energy of a wave results from the amplitude of displacement from the neutral position of all the water particles involved in the wave motion. Since inter-molecular friction in water is negligible, the amount of energy in a wave remains practically constant till modified by external influence.

2. A wave entering shoaling water transfers practically all its energy to a smaller and smaller number of particles.[2] These fewer particles are therefore displaced to a greater amplitude and so travel in larger and larger orbits to produce higher and steeper waves.

3. The velocity of a wave in shallow water depends upon the depth, according to the standard formula,

$$v = \sqrt{gd}$$

where d = depth, and g = acceleration of gravity. So as the water becomes shallower, the *velocity* of the wave *decreases*. This results in shortening the wave-length, λ,

$$v = n\lambda$$

for the frequency, n (i.e., the number of waves passing a point during a given time) by observation remains constant.

4. Since the frequency remains constant, each particle must describe its larger orbit in the same time as it did its smaller one, and hence must have greater orbital velocity. This orbital velocity becomes greater and greater while, due to the shortening wave-length, the forward motion of the wave becomes slower and slower. When the orbital velocity of the particles in the upper part of the water becomes greater than the forward propagation of the wave, the wave breaks.

[1] The orbits are ellipses under certain conditions, but for the purpose of the present discussion circular orbits will suffice.

[2] Friction on the bottom is of little importance.

STUDIES FOR STUDENTS

A BRIEF VIEW OF ROCKY MOUNTAIN STRUCTURE

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ABSTRACT

The available information concerning the structure of the Rocky Mountains is briefly reviewed, with special reference to those sections which show structures dipping in under the ranges from both sides. It is pointed out that the close-folding and overthrusting entail a compressional origin for the system as a whole. In consequence of the observations and experiments of R. T. Chamberlin, it is suggested that the Rocky Mountains may have developed in a series of two-sided zones, in response to compressional stresses.

The Rocky Mountain System may be considered as forming the eastern flank of the great Cordilleran system from the Endicott Range at Bering Sea more or less continuously to Central New Mexico. Daly[1] has included in the Rocky Mountain System the Rockies proper and their genetic continuations and extensions both north and south; Ransome[2] includes also the ranges west to and including the Gold Range in British Columbia and the Mission and Wasatch Mountains in the United States, and takes in also the San Juan and Sangre de Cristo ranges in Colorado. R. T. Chamberlin[3] would agree with Daly in setting the Rocky Mountain Trench as the western boundary of the Rockies in Canada, and bounds the system on the south by the end of the single Sangre de Cristo ridge, leaving out the San Juans altogether. This is a more natural classification, inasmuch as the San Juans are not structurally related to the Rockies.

Further evidence for the structural unity of the Rocky Mountain group as above defined, in connection with Chamberlin's theory of wedge-shaped zones of deformation,[4] is to be had in the presence of structures dipping east under the mountains in the Rocky Mountain

[1] R. A. Daly, *Geog. Jour.*, Vol. XXVII (1906), p. 586.

[2] F. L. Ransome, *Problems of American Geology*, Yale, 1915.

[3] R. T. Chamberlin, *Jour. of Geol.*, Vol. XXVII (1919), pp. 147–48.

[4] *Ibid.*, Vol. XVIII (1910), p. 228; Vol. XXIX (1921), p. 416.

Trench in Canada,[1] at the west bases of the Mission Range,[2] the Bitterroots,[3] the Wind River Mountains,[4] and the Wasatch[5] Mountains. These structures will be discussed later.

Throughout Alaska and Canada, the system preserves a symmetry developed in long parallel ridges, changing only in trend, from east-west in the Endicott Range gradually to northwest-southeast farther south. In Montana, however, this arrangement breaks up, and the Rockies gradually come to be represented by irregular mountain groups such as the Bridger, Big Snowy, and Big and Little Belt mountains, some of which are the result of igneous intrusions. From western Wyoming south through Colorado and New Mexico, the ranges exhibit a more orderly plan, those on the west converging with the eastern ridges to form a rough letter Y, somewhat broken by an *en echelon* pattern (Fig. 1).

Structurally, the system as a whole exhibits varying characteristics. The eastern border of the Rockies in Canada where well known, and in northern Montana, is marked by great overthrust faults. Farther west it is characterized by folding, although local overthrusting is very important. From southern Wyoming to the southern end of the Rockies, open folding is the structure dominating the whole group. While considerable portions of the Rocky Mountains thus exhibit similar structural characteristics over wide areas, there are nevertheless local differences and peculiarities which are interesting both in themselves and in the fact that they may throw light upon the forces which deformed the whole vast region. Since broad-scale information is not to be had, local studies must be considered and correlated as nearly as possible.

THE NORTHERN ROCKIES

Very little is known concerning the structure of the Rockies of Alaska and Northern Canada. The ranges appear to be continuous, both topographically and structurally, with those in Southern

[1] F. P. Shepard, *Jour. of Geol.*, Vol. XXX (1922), p. 130.

[2] Roy Wilson, "Geology of the Mission Range," *Bull. Montana Bureau of Mines.* (In press.)

[3] W. Lindgren, *U.S. Geol. Survey Prof. Paper 27* (1904), p. 26.

[4] Eliot Blackwelder, *Jour. of Geol.*, Vol. XXIII (1915), p. 101.

[5] Eliot Blackwelder, *Bull. G.S.A.*, Vol. XXI (1910).

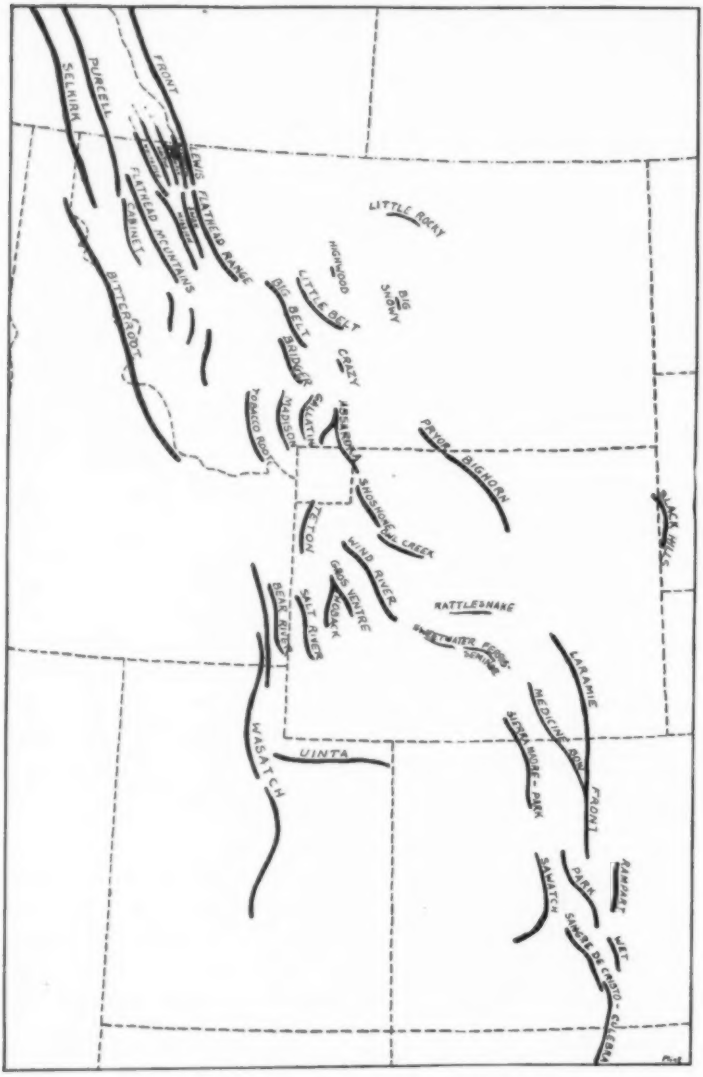

FIG. 1.—Principal tectonic ranges of the Rocky Mountains

Canada; and if the few available sections may be correlated over such great distances, they indicate a continuity of structure.

As authority for structure in the Rockies of Southern Canada, we have McConnell,[1] Allan,[2] Daly,[3] and Shepard.[4] In this region, the Rockies appear to be bordered on the east and west by thrust faults dipping in under the ranges. This suggests movement outward from a center within the mountains themselves. In a section[5] compiled from various authors, and extending from the Rocky Mountain Trench eastward through the Front Range for a distance of approximately 80 miles, the center of movement is apparently located about 25 miles from the western limit. This asymmetry is

FIG. 2.—Section across the Canadian Rockies (Root)

FIG. 3.—Mechanical representation of the deformation shown above

carried out by the dip of the thrust-planes which, being more gentle in the long eastern arm than in the short western arm, may be mechanically diagrammed as shown above (Fig. 3). The major thrust on the east is further complicated by numerous slice-blocks. The strata in the faulted blocks are folded, and the folds are found by reconstruction to have composed a synclinorium, more intensely folded at the eastern and western extremities, where the major faults now are, than in the central area, where less

[1] R. G. McConnell, *Ann. Rept. Geol. Surv. Canada*, 1886, Part D.

[2] J. A. Allan, *Geol. Surv. Canada Guide Book 8*, Part 2, 1913; *ibid., Memoir 55* (1914), pp. 198–204.

[3] R. A. Daly, *Geol. Surv. Canada Guide Book 8*, Part 2, 1913, pp. 149–50.

[4] F. P. Shepard, *op. cit.*

[5] T. B. Root, *A Section across the Canadian Rockies*, Master's thesis, University of Chicago, 1922.

subsequent displacement has taken place. Allan[1] believes that this folding antedated the faulting by a considerable lapse of time. If he is correct, it seems probable that these folds localized the later faults and determined their nature: and if his assertion is wrong, it appears reasonable that the faults were a direct contemporaneous outgrowth of the folding, caused by the same force, which could be no longer withstood without displacement. And in the former case, even if there were two very distinct periods of movement, both structures may well have originated in the same manner, and at the same place.

Daly[2] states that the folding took place in Laramide times, so that by the beginning of the Eocene the Canadian Cordillera had their maximum extent. Shepard concedes the Laramie age of the folding, but asserts that the faulting in the vicinity of the Rocky Mountain Trench occurred after most of the folding. Daly further considers the overthrusts in northern Montana contemporaneous with those farther north.

To the west, in the Purcell and Selkirk ranges, Daly[3] has mapped several faults of considerable magnitude, which cut great thicknesses of folded strata; but the reconnaissance nature of the field work has made it impossible definitely to determine their exact character.

Probably continuous with the faults along the eastern front in Alberta is the Lewis overthrust[4] in northern Montana, extending north into Canada and south beyond the parallel 48°30′. Here Proterozoic rocks are overthrust eastward upon Cretaceous sediments. The Lewis plane is shown to be an undulating surface, probably indicating a continued compressive stress effective even after friction had set a limit to movement along the fault plane. Willis would assign conditions of deposition of the sediments as cause of the localization of the deformation.

Stebinger[5] has recognized the Lewis thrust in the vicinity of the Blackfeet Indian Reservation, where it forms the western limit of a

[1] J. A. Allan, *Geol. Surv. Canada Memoir 55*, pp. 199–208.

[2] R. A. Daly, *Geol. Surv. Canada Guide Book 8*, Part 2, 1913, pp. 161–62.

[3] *Geol. Surv. Canada Memoir 59*, 1915.

[4] Bailey Willis, *Bull. G.S.A.*, Vol. XIII (1901), p. 306.

[5] Eugene Stebinger, *U.S. Geol. Survey Bull. 691-E*, p. 172.

20-mile zone of intense deformation characterized mainly by reverse faults grading eastward into open folds. Toward the south, the deformation becomes both less widely distributed and less intense, consisting mainly of folds with faults subordinate. This belt of disturbed rocks forms a structural province extending north through Alberta and south at least as far as the Dearborn River.

LACK OF CONTINUITY IN THE EASTERN RANGES

So far, a definite eastern "front" has been distinctly traceable. Southward, smaller ranges usually linear appear, marring the sharp transition from Great Plains to Rockies. The Belt Ranges and the Bridger, Madison, and Gallatin ranges besides the outlying Big Snowy and Crazy mountains occur in Montana, while in Wyoming, all semblance of a continuous front has disappeared, leaving in its place the irregularly striking Teton, Shoshone, Owl Creek, and Bighorn Mountains. Concerning many of these masses, little is yet known. Certain of them present variations to the prevailing structure hitherto encountered, inasmuch as the Crazy and High wood Mountains owe their presence to igneous intrusions. According to Lupton and Lee[1] the Big Snowy and Judith mountains and the Porcupine Dome form an independent anticlinorium which may be genetically connected with the Little Belt Mountains. The latter occur in the form of a broad, flat-topped arch,[2] bounded on the southwest by a rather steep eastward overthrust, indicating movement from the west.

Thom[3] considers the change from the simple structure of the Rockies farther north, to the complex conditions referred to above, not the result of differently acting forces, but rather the effect of older deep-seated structures upon the Laramide thrusts. As one evidence for such modification, Thom cites the presence of the Boulder Batholith as having determined the convergence of two sets of mountain trends. Farther east, he would attribute the lack of typical Rocky Mountain structure to the presence of later Paleozoic and Mesozoic east-west faults and arches, presenting

[1] C. T. Lupton and W. Lee, *Amer. Assoc. Petrol. Geol. Bull.*, Vol. V (1921), p. 269.

[2] W. H. Weed, *Little Belt Mts. Folio, U.S. Geol. Survey* text and sections (1899).

[3] W. T. Thom, Jr., *Amer. Assoc. Petrol. Geol. Bull.*, Vol. VII (1923), p. 4.

structural buttresses to the thrust which farther north was unimpeded. To magmas rising along such older fault planes during the Laramide movements are assigned the intrusions of the Crazy and Highwood mountains, and of numerous smaller domes believed to be laccolithic.

Davis[1] has characterized the Bridger Range as a fold strongly overturned to the east, dips on the western flank being 60 to 70 degrees west. Thick Carboniferous limestone here seems to have been the competent bed.

Overturning, however, does not represent the greatest degree of deformation in this region. For 35 miles continuously along the northeastern flank of the Beartooth Mountains, an overthrust has been found by Calvert,[2] and has been more recently recognized by Bevan[3] as the Beartooth Fault. The structural details have not been worked out, although the horizontal component seems to have been less effective here than in the overthrusts farther north.

Directly east of Yellowstone Park a similar displacement occurs, known as the Heart Mountain overthrust. Later volcanics cover so much of the area that the relations may never be worked out in detail, but a few facts are apparent. The overthrust block, about 15,000 feet thick, is relatively simple and undeformed, and has been moved eastward more than 30 miles,[4] the effective stratum being the Madison limestone. The floor of the overthrust is composed of sharply folded and truncated rocks, indicating the effects of pressure before relief was found in faulting. Dake[5] describes a local fault, the South Fork Thrust, which occurs below the main Heart Mountain fault. The time-relation between the two displacements is undetermined. The maximum length of the lower fault is 8 miles. The thrust-plane, striking northwest, is sharply folded along a northeast-southwest axis and is locally even overturned. These phenomena taken as a whole suggest strong deformation both before and after the actual fracturing, with a later change either in

[1] W. M. Davis, *Tenth Census*, Vol. XV (1886), pp. 705–6.

[2] W. R. Calvert, *U.S. Geol. Survey, Bull. 641*, p. 205.

[3] Arthur Bevan, *Jour. of Geol.*, Vol. XXXI (1923), p. 441.

[4] D. F. Hewitt, *Jour. of Geol.*, Vol. XXVIII (1920), p. 536.

[5] C. L. Dake, *Jour. of Geol.*, Vol. XXVI (1918), p. 51.

the direction of the greatest force, or in the response of the rocks to the stress produced. Bevan thinks that the Heart Mountain and Beartooth faults are genetically very closely related, and Hewitt[1] considers the Heart Mountain deformation correlative with the Lewis Thrust. It remains for further study to prove or disprove these relations.

The Bighorn Mountains are described as being one of a series of crests initiated by compression applied in the Yellowstone Park region, and heightened by the resulting unequal loading. The Beartooth Plateau and the Black Hills are possibly related to the Bighorns in such a series. Thom[2] attributes these uplifts to a combination of simple folding under compression, isostatic adjustment, and contributory tangential thrust, the latter being probably introduced to account for the lack of symmetry apparent in the Bighorn and Black Hills uplifts. Both show much-steepened eastern flanks.

Southward in Wyoming are found other isolated ranges: the Rattlesnake Range, the Ferris Mountains, Seminoe Mountains, Granite Mountains, and the Casper, Clearwater, and Haystack ranges. Darton[3] describes the structure of central Wyoming in general terms as a series of elongate flexures extending east and west. The mountains above referred to, with associated uplifts, are to be explained on this basis. The peculiar trend of these structures, and the fact that they represent no very great deformation, implies some disturbing factor affecting the Laramide forces, either similar to that postulated by Thom, or some quite different phenomenon.

THE SOUTHERN ROCKIES

Not far south of Casper, however, the simpler structure is resumed in the appearance of the Laramie Mountains, an extension of the Front Range of Colorado, striking almost due south. This range owes its presence to a simple asymmetrical fold indicating thrust from the west. The dips are very gentle on the west and steep on the east flank, and are locally even overturned. One or two slight overthrusts may be present.[4] Others might possibly be

[1] D. F. Hewitt, *op. cit.*

[2] W. T. Thom, Jr., *op. cit.*, p. 5.

[3] H. H. Darton, *Laramie-Sherman Folio, U.S. Geol. Survey* (1910), text, p. 11.

[4] *Ibid.*

determined if the slopes were not for the most part covered with recent deposits.

South of the Wyoming-Colorado line, the asymmetry of the folding becomes gradually less well marked, the arch becomes far more complex and irregular, and the width of the folded belt increases. On the east, in the vicinity of Boulder, the Boulder Arch[1] is not less than 2 miles high, if erosion be disregarded. In this section the pre-Cambrian core of the Rockies is exposed in a belt about 35 miles wide, with Paleozoic and Mesozoic sediments dipping steeply on its flanks (Fig. 4). Parallel folds of less imposing size are found to the west, disappearing westward in the Uinta Basin. The entire series of folds, measured from Lyons to Glenwood Springs, covers a distance of 132 miles.[2]

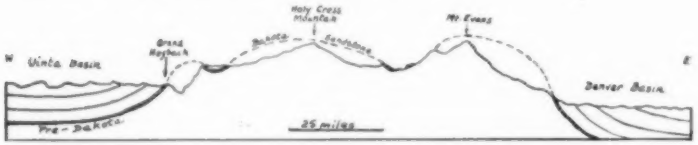

FIG. 4.—Section across the Colorado Rockies (Lee)

Three main ranges extend southward from the latitude of Denver: the Rampart Range on the east, the Park Range, and the Sawatch Mountains–Cochetopa Hills on the west. Open folding is generally characteristic of the region, but in the foothills near Colorado Springs, Finlay[3] has mapped the Ute Pass fault, extending irregularly south-southeast for a distance of about 20 miles, throughout which pre-Cambrian granite is brought into contact with Cretaceous and older sediments. The relations are given as those of a thrust fault dipping westward at an angle of about 50 degrees. It is noted, however, that this condition may have been brought about by subsequent tilting of a normal fault plane.

The Sawatch and Sangre de Cristo–Culebra ranges form a fairly well-defined structural unit. The jog in trend between the Sangre de Cristo and Culebra ranges probably does not indicate a typical

[1] N. M. Fenneman, *U.S. Geol. Survey Bull. 265* (1905), p. 41.

[2] R. T. Chamberlin, *Jour. of Geol.*, Vol. XXVII (1919), p. 231.

[3] G. I. Finlay, *Colorado Springs Folio, U.S. Geol. Survey*, 1916.

en echelon fold, but is marked by a granite mass, the Sierra Blanca massif, to which it may owe its presence. The central part of the Sangre de Cristo Mountains shows a definite eastward thrust fault, with a plane dip of from 55 to 60 degrees and a known linear extent of 20 miles. Approximately parallel with it is a second thrust of the same general character (Fig. 5). Intense compression, expressed in less open folding, is evidenced for a distance of 30 miles throughout the central part of the range, gradually lessening both northward and southward. Northwest of the West Spanish Peak, the Cretaceous strata at the east base of the Culebra Range are overturned as much as 25 degrees.[1]

The Wet Mountains, east of the Sangre de Cristo, consist of a doubly plunging anticline overturned toward the east. At their

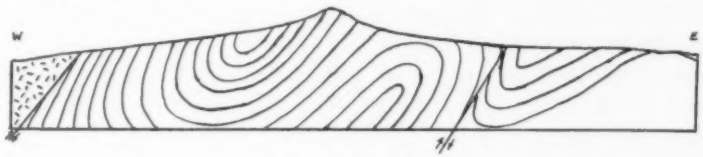

FIG. 5.—Section across the central part of the Sangre de Cristo Range (Melton)

southern end they exhibit a simple anticlinal cross-section. Of the more northern part, Washburne[2] says that the strata at the eastern base are sharply upturned, probably due to a thrust fault. This fault completely overturns the beds in the southern part of the Canon City Coal Field, where pre-Cambrian granite rests upon Cretaceous strata.

The Culebra Range continues southward into New Mexico. In the southern part, north of Las Vegas, the more easterly folds are steeper on their eastern flanks than on the western, the front range fold proper being locally overturned and thrust-faulted.[3] South of Las Vegas, the range gradually disappears, probably as a result of southward pitch in the structure, with dying out of the thrusting effect. Near its southern extremity it exhibits in section a simple anticline.

[1] F. A. Melton, personal communication.

[2] C. F. Washburne, *U.S. Geol. Survey Bull. 381*, p. 342.

[3] C. L. Baker, *Amer. Jour. Sci.*, Vol. XLIX (1920), p. 99.

THE WESTERN ROCKIES

Having considered the structures forming the eastern flank of the Rockies, we may now begin again in the north and examine the structures lying farther west. The Galton, Flathead, and Whitefish ranges in Montana and British Columbia are shown by Daly to be the product of rather extensive normal faulting.[1] It must be understood that this interpretation is based on rather rapid reconnaissance, and may be considerably modified in the future. North of the Bridger Range, Haynes[2] has described the Lombard overthrust, at least 13 miles long, with a horizontal eastward displacement of more than 2 miles along a plane dipping as much as 40 degrees. The fracture must have been uneven from its inception, since at its north end, rocks of the Belt series rest upon Cretaceous strata, while farther south, upper Cambrian beds overlie Mississippian (Madison) limestone. These facts may be cited in further support of Thom's theory of the local control of Laramide deformation by earlier structures. The trend of the structure here, north-northeast, may also be connected with such phenomena.

South of this fault, in the Three Forks District, there is close folding, locally isoclinal,[3] which Haynes considers to be related to the Lombard thrust, although definite correlation has not yet been made.

West of Lombard, in the vicinity of Philipsburg the structures also strike north-northeast. There are two notable eastward overthrusts, the Philipsburg and the Georgetown respectively, in both of which Proterozoic (Newland) strata have been forced over Pennsylvanian (Quadrant) beds, along planes essentially parallel to the stratification. A comparison of the strata involved in each of the overthrusts referred to in the preceding pages indicates the importance of the part played by competent beds in such movements. In no case has a weak formation carried the thrust. Other minor overthrusts occur in the Philipsburg area, as well as a number of steep-angle reverse faults, doubtless the product of the general force.

[1] R. A. Daly, *Geol. Surv. Canada Memoir 38*, 1912.

[2] W. P. Haynes, *Jour. of Geol.*, Vol. XXIV (1916), p. 269.

[3] A. C. Peale, *Three Forks Folio, U.S. Geol. Survey*, 1896; *ibid., U.S. Geol. Survey Bull. 110*, 1893.

which produced the overthrusts. Emmons and Calkins[1] think that the strain attendant upon the elevation of the Rocky Mountain region produced extensive north-south fissures with gentle, westerly dips, and that lateral pressure was relieved by thrusting of the more elevated western portion over the lower mass to the east. Horizontal movements were halted by continued lateral pressure, which warped the fault planes and thus increased the friction sufficiently to arrest motion.

In western Wyoming, southeastern Idaho, and northeastern Utah are a series of folds and thrust faults repeating the same type of structure already described, indicating horizontal movement eastward. From the vicinity of Logan, Utah, northward irregularly through the Bear Lake district for 270 miles to a point northeast of Pocatello, Idaho, the Bannock overthrust has been traced as a practically continuous feature.[2] The thrusting has taken place in an eastward direction, through not less than 12 nor more than 36 miles. The vertical displacement, 8,500 feet at a maximum, diminishes eastward as a result of branching of the fault. As in the case of similar thrusts, the fault-plane has undergone considerable subsequent deformation. The Putnam overthrust[3] lying slightly west of the northern end of the Bannock is probably directly associated with it, as are also the Snake River and Crawford faults, which lie east of the Bannock in the vicinities of Pocatello and Logan, respectively.

Farther east, in western Wyoming, lie the parallel Absaroka and Darby faults.[4] These have been studied less intensively than the Bannock; but both indicate that the forces producing them have acted somewhat less horizontally, although the displacement eastward is again large, probably exceeding 25 miles. Still farther east the same compression seems to have resulted in the folds of the Gros Ventre and Hoback ranges, which trend generally north-south. Actual fracture seems here not to have taken place. Within the zone of the overthrust area, there are parallel structures consisting

[1] F. C. Calkins and W. H. Emmons, *Philipsburg Foilo, U.S. Geol. Survey*, 1915.

[2] R. W. Richards and G. R. Mansfield, *Jour. of Geol.*, Vol. XX (1912), p. 685.

[3] G. R. Mansfield, *Bull. G.S.A.*, Vol. XXXIV (1923), p. 267.

[4] A. C. Veatch, *U.S. Geol. Survey Professional Paper 56*, 1907.

of synclinoria with relatively narrow intervening anticlines, usually asymmetrical, inclined or overturned to the east and northeast.[1]

INDICATIONS OF WEDGE-SHAPED DEFORMATION

The easternmost unit of the northern Rockies is bounded on the east by the front range thrusts in Alberta, and the Lewis thrust and associated structures which show tangential pressure directed eastward, in the vicinity of the Belt ranges. In Canada the western limit of this unit is the Rocky Mountain Trench already referred to[2] which shows westward structures. The latter seem to find their counterpart in the Mission Range of Montana, where Wilson has found structure indicative of westward movement; and in the ranges eastward to the Continental Divide, where the same observer has noted several small but pronounced eastward-dipping thrust faults. Wilson believes that the evidence in this region is indicative of distinct wedge-deformation.[3] It appears likely that more detailed work in southwestern Montana may reveal a further continuation of this relationship.

Another distinct unit in the Rockies of this latitude is represented on the one side by the eastward compression shown in the Philipsburg district, with its continuation northwestward and southeastward on a less intense scale; and on the other side by the fault mapped by Lindgren[4] in the Bitterroot Mountains, strongly suggesting compression toward the west.

Thus, if we may be allowed to generalize on the strength of evidence which is still necessarily local, we find two parallel zones which apparently indicate a thrusting upward and outward in both directions from the north-northwest-trending axis of each. The age relations of these zones cannot yet be determined, beyond the fact that in general they appear to be contemporaneous. Their character in northern Wyoming and northeastern Idaho is very obscure because of the lack of continuity of the ranges, and in the Yellowstone Park region particularly because much of the structure

[1] A. R. Schultz, *U.S. Geol. Survey Bull. 543*, 1914.

[2] G. R. Mansfield, *Jour. of Geol.*, Vol. XXIX (1921), p. 446.

[3] Roy Wilson, personal communication. Details of this structure are soon to be published.

[4] Waldemar Lindgren, *U.S. Geol. Survey Professional Paper 27*, 1904.

has been concealed beneath later volcanics. We do find, however, indications of the same zonal arrangement farther south in Wyoming. On the east are the anticlines of eastern and central Wyoming, while in the western part of the state the Wind River Range, trending southeast, shows pronounced overturning on its *southwestern* flank. While it may be argued that this is the result of underfolding during an eastward thrusting movement, it seems more consistent with experimental results in the production of folds that this is the normal overturn produced through a westward tangential thrust. Further work, both in the field and in the laboratory, will be necessary in order to establish this point conclusively.

Southeast of the Wind River Mountains, and essentially continuous in trend, lies the Sweetwater uplift, exhibiting local overthrusting. For example, the Sheep Mountain anticline, trending east-southeast, is overthrust on its southwest flank *toward* the south and west.[1] About 40 miles farther southeast, along the strike of the uplift, appear the Ferris and Seminoe mountains, on the southwest flanks of which the strata are vertical or even slightly overturned.[2] Southeast of the Ferris mountains, this sharp folding gives way to thrust-faulting with movement toward the southwest. Fath[3] thinks that this faulting probably continues eastward to the Freezeout Hills, a distance of at least 25 miles. He considers the Ferris and Seminoe mountains a marginal rim to the Sweetwater uplift, developed at a somewhat later time.

West of this region, we find evidence of still another zone of two-sided deformation. In southeastern Idaho, the Bannock-Absaroka-Darby series of overthrusts already described, together with the Uinta thrusts[4] at the north base of the Uinta Mountains, give evidence of strong compressive stress resulting in fractures forming roughly the letter L, the movement being eastward on the long limb (Bannock thrust, etc.) and northward on the short limb (Uinta thrusts). This northeastward movement finds its counterpart in the Wasatch Mountains to the west. Here, between Logan

[1] C. J. Hares, *U.S. Geol. Survey Bull. 641*, 1917, p. 251.

[2] A. E. Fath, *Jour. of Geol.*, Vol. XXX (1922), pp. 303–10.

[3] *Ibid.*

[4] A. R. Schultz, *U.S. Geol. Survey Bull. 690*, 1918, pp. 69–74.

and Salt Lake City, Blackwelder[1] has described the Willard overthrust, at least 22 miles long, with a maximum horizontal displacement of 4 miles. Proterozoic strata have been thrust *westward* over Paleozoics. This fault has not been worked out in detail, and further investigation may show its extent to be considerably greater. It seems probable that the Alta overthrust,[2] in the Cottonwood district south of Salt Lake City, which also has an eastward-dipping, though steep, plane, may be associated with the Willard fault. It should be noted that Calkins[3] believes the original dip of this fault plane to have been westward, and that the movement was, therefore, toward the east rather than toward the west.

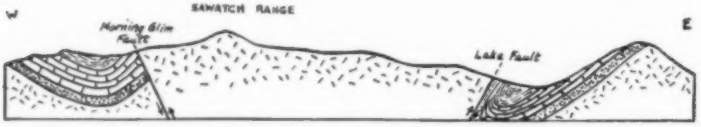

FIG. 6.—Section across the Sawatch Range (Crawford)

Evidence for other similar two-sided zones is not lacking. Near Garfield, in south central Colorado, the Sawatch Range, trending north and south, is bounded on both sides by thrust faults which dip in under the range (Fig. 6).[4] These parallel faults have a longitudinal exposure of only about 2 miles where an extensive blanket of later volcanics fails to cover the flanks of the range, and no idea of their total extent can be gained. There is evidence, however, that the easternmost of the faults passes southward into a sharp synclinal fold.

Another zone occurs farther south, between the Wet Mountains and the Sangre de Cristo Range. The eastward thrusting observed along the east base of the Wet Mountains limits this zone on the east, while on the west it is bounded by the westward thrust at the east base of the Sangre de Cristo Range.[5] This fault has been mapped through a distance of more than 10 miles on either side of the

[1] Eliot Blackwelder, *Bull. G.S.A.*, Vol. XXI (1910), p. 517.

[2] G. R. Mansfield, *Bull. G.S.A.*, Vol. XXXIV (1913), p. 269.

[3] *Ibid.*

[4] R. D. Crawford, *Colorado Geol. Surv. Bull. 4*, 1913, p. 91.

[5] M. R. Campbell, *U.S. Geol. Survey Bull. 707*, 1922.

Arkansas River, a few miles east of Salida, and is shown to have a steep dip. Campbell[1] states that while the evidence is not conclusive, pre-Cambrian crystalline rocks have in all probability been thrust westward over late Paleozoic sedimentaries. *En echelon* with this fault, and only a few miles west of it, occurs the *eastward* overthrust described by Melton. The strata between the two faults are synclinal, as will be seen in a comparison of the sections of Campbell and Melton. Whether or not Melton's fault bounds another more westerly zone of two-sided deformation is not known, and indeed may never be determined, since the important structure west of this area is covered largely by later lava flows and sediments.

DEDUCTIONS AND CONCLUSIONS

In plotting on a grand scale the trends of the folds and faults which make up the Rocky Mountains, interesting phenomena are brought out. Two distinct zones of two-sided folding seem to parallel each other discontinuously from southern Alberta to Colorado (Figs. 7 and 8). Their trend is not uniform, but changes in Utah and Wyoming to a distinctly east-west direction. This may be explained by assuming either a change in direction of the actual force involved, or an altered response to the stress, resulting from (1) previously existing structures, or (2) conditions of sedimentation. Associated with these facts may be the observed differences in the character of the structure in different parts of the system. Within Colorado, says R. T. Chamberlin,[2] the Rockies are characterized by open folding, moderate crustal shortening, affecting a deep zone, by strong uplifting, and by the extrusion of much lava, while in Montana and Alberta there is low-angle thrust-faulting, greater crustal shortening, and less volcanic activity.

Various authors have attempted to explain the Rockies and similar systems in various ways. A brief consideration of certain of these theories may well be taken up here.

Lee,[3] considering only the southern Rockies, compares them to raised blisters rather than to wrinkles of the earth's crust. He

[1] M. R. Campbell, personal communication.

[2] R. T. Chamberlin, *Jour. of Geol.*, Vol. XXVII (1919), p. 251.

[3] W. T. Lee, *Bull. G.S.A.*, Vol. XXXIV (1923), p. 285.

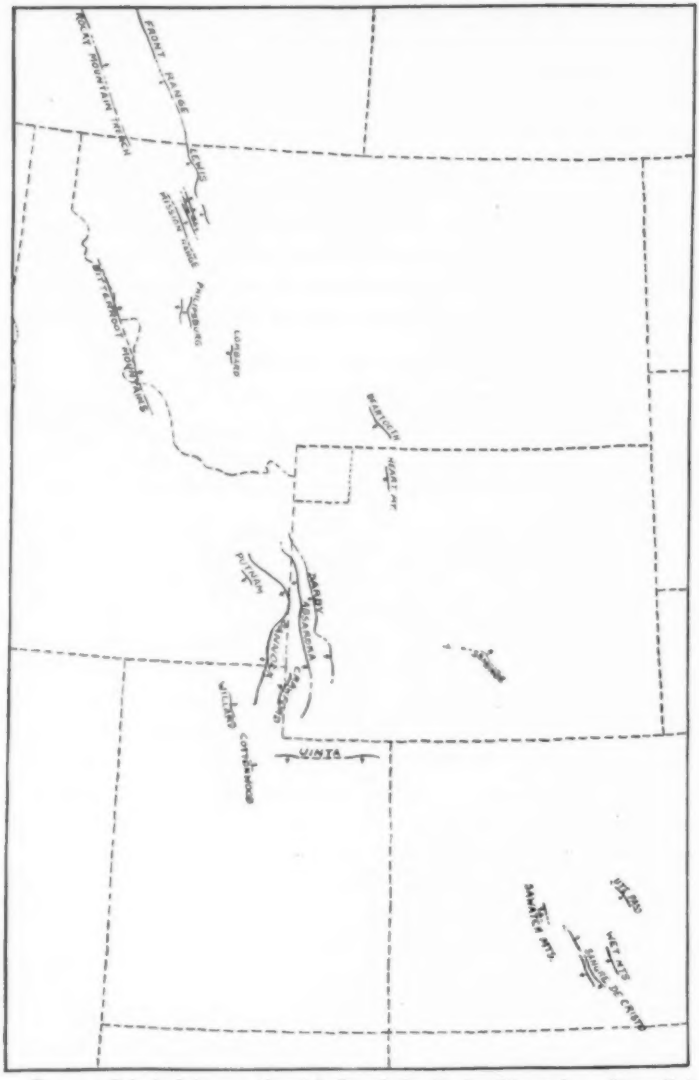

FIG. 7.—Principal known thrust-faults of the Rocky Mountains. (Compiled from various maps and communications.)

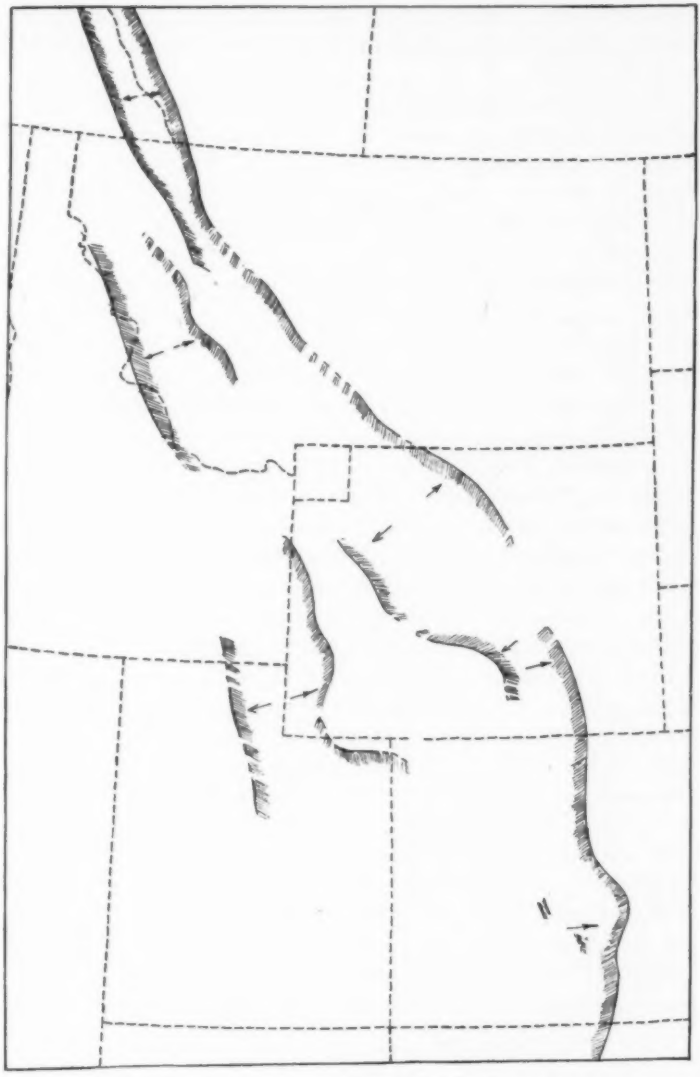

FIG. 8.—Zones of deformation in the Rocky Mountains

invokes isostatic adjustment as the cause of the movement, the effective component of which must then have operated vertically upward.

Keith[1] explains the structure of the Appalachian system on a basis of batholithic intrusions moving upward and outward, thus by hydrostatic pressure producing vertical and horizontal motion. While he does not extend this explanation to include the Rocky Mountains, he likens the Appalachian folds to the folds of the Rockies.[2]

The folding and overthrusting in the Rocky Mountains indicate clearly that *compression* has been the dominant factor in their building. The insurmountable difficulty met with in the application of the two foregoing theories is that both necessarily involve stretching rather than compression, so that the facts deduced from the great mass of field evidence are not merely not confirmed: they are reversed. Neither theory therefore can be harmonized with present knowledge of Rocky Mountain structure.

Kober[3] has recently advanced an ingenious though complicated theory of Alpine structure which he applies to all the folded ranges of the globe. His conception is based on the existence of great rigid plates or shields, continental in size, which, under the influence of lateral compression, force the intervening plastic geosynclines to ride upward and outward over the rigid masses.

In applying this theory to the Rocky Mountains, Kober takes the entire Cordilleran system as his unit, ignoring the fact that the whole Basin Range area does not structurally bear out his thesis. Theoretically, however, there are points in Kober's explanation which may well be included in a consideration of Rocky Mountain structure. The sequence of events just outlined coincides with Schuchert's statement[4] that the Rocky Mountain geosyncline has been very mobile. It was a zone of gradual subsidence from the Triassic to the end of the Lower Cretaceous, received sediments throughout the Upper Cretaceous, at the close of which time it was converted into land and deformed. Schuchert goes on to cite the

[1] Arthur Keith, *ibid.*, p. 309.

[2] *Ibid.*, p. 347.

[3] Leopold Kober, *Der Bau der Erde*, Leipzig, 1921.

[4] C. S. Schuchert, *Bull. G.S.A.*, Vol. XXXIV (1923), p. 191.

fact that in Idaho, western Montana, British Columbia, and Alberta there is no evidence that orogenetic movements took place between the very early Proterozoic and the close of the Cretaceous. The continuous series of sediments, some 14 miles thick, indicates that the earth's crust may continue to subside locally through at least this distance, before it becomes folded into mountains.

Kober's theory is based on horizontal compression, the tangential thrust which seems absolutely necessary to account for the phenomena described. It also gives one explanation for the two-sided zones which appear to be well-defined in certain Rocky Mountain areas. While thrusts throughout the entire system have in the past been considered as originating in the Pacific, this hypothesis suggests a reasonable cause for thrusts directed in opposite directions, which have hitherto been unaccounted for. Certain facts, however, still remain unexplained: (1) How can the presence of two parallel orogenetic zones, very close together, be reconciled with the theory of great rigid continental plates? It is difficult to conceive of the accumulation of any great force in the narrow strip between two zones such as are found in the Rockies. (2) Even if the foregoing be explained, is the Great Basin area to the west sufficiently large to have formed a continental plate such as is described by Kober?

Hobbs[1] has argued that underthrusting rather than overthrusting has been the dominant response to tangential pressure in the building of such mountain chains as the Rockies. Contrary to the view held by Suess,[2] he believes that thrusting has been directed from the areas of deposition and subsidence (i.e., the seas) *toward* the land. He says:

> The mountain arcs face the sea, not because the land is thrusting itself seaward within the continental areas behind them; but because the strata beneath these sinking sea-bottoms at their front find themselves ever more closely pinched because of their settlement, and in consequence are exerting a thrust outward against the continent.

Underfolding and underthrusting are the result, yielding seaward-moving structures.

In experimental support of this theory, Hobbs gives the results of a series of experiments in which Canada balsam was cooled upon

[1] W. H. Hobbs, *Jour. of Geol.*, Vol. XXII (1914), p. 206; *Earth Evolution and Its Facial Expression*, New York, 1921.

[2] Edouard Suess, *The Face of the Earth.*

a stretched rubber membrane. When the latter was allowed to contract, arcuate wrinkles in the balsam formed convex to the direction of centripetal force. R. T. Chamberlin and F. P. Shepard,[1] however, have later shown that under experimental conditions, (1) overfolding rather than underfolding tends to develop as a result of lateral compression; (2) arcuate wrinkles will form under force applied centrifugally as well as centripetally, the wrinkles in either case tending to form more or less normal to the compression; (3) arcuate folds which are concave rather than convex to the direction of force can be easily produced. As Mansfield[2] points out, it is much easier to imagine thrusts moving upward and outward, in the direction of least resistance, than to believe that weak beds could be forced downward into areas of far greater resistance. Under Hobbs's theory, dislocations should be oldest on the east, becoming successively younger in a westward progression across the Rockies until the youngest structure produced by forces from the other side be reached. The ages of the observed structures do not seem to coincide with such an arrangement. Mansfield states, in fact, that the Heart Mountain thrust and possibly the Lewis thrust on the east are younger than the Bannock fault, which in turn is thought to be younger than the Philipsburg faults. These facts denote an arrangement exactly the reverse of the one called for by Hobbs's theory.

The major structures throughout the Rockies are indicative of lateral compression. Normal faults are common, it is true, but in a great many instances they can be shown to be the result of readjustive settling following response to compression. If the interpretation be correct that these mountains have undergone growth in two-sided zones, such a zone might be structurally diagrammed as in Figure 9. Tangential thrusts, directed toward each other, would result in deformation and dislocation along planes of weakness in the area against which the thrusts were being directed.[3] Becker says:[4]

[1] R. T. Chamberlin and F. P. Shepard, *Jour. of Geol.*, Vol. XXXI (1923), p. 490.

[2] G. R. Mansfield, *Bull. G.S.A.*, Vol. XXXIV (1923), p. 272.

[3] A. Daubrée, *Études Synthetiques de Geologie Experimentale.*

[4] G. F. Becker, *Bull. G.S.A.*, Vol. IV (1893), p. 50.

A direct, uniformly distributed pressure, of sufficient intensity, applied to an elastic brittle mass presenting great resistance to deformation, would induce fracture. The ruptures would take place along those lines subject to the greatest tangential strain, since these are the directions in which material would be strained beyond endurance. These would stand at 45 degrees to the line of force if the mass presented infinite resistance to deformation.

Two-sided zones of this type in an area of general deformation would be likely to be located by synclinal troughs, by local variations in the character of the strata resulting in relatively thinner and less competent beds, and also possibly by the presence of previously existing structures. The areas between the zones would then be buttress-like in origin, determined for the most part by greater competency

FIG. 9.—Diagram showing response to compression in mountains undergoing growth in two-sided zones.

of the rocks. This conception does not rule out the possibility of underfolds. Under experimental conditions, underthrusting has been found to occur subordinately to overthrusting. In the northern part of the Sangre de Cristo Range two thrusts dipping steeply in opposite directions have been shown to be aligned very closely with each other. The deformation here, as far as can be determined from present information, may have consisted in part of an underthrust.

R. T. Chamberlin has shown that in such folded zones as the Appalachian Mountains of central Pennsylvania[1] and the Colorado Rockies[2] the zones affected by folding are wedge-shaped;[3] and while the actual mechanics of the formation of such zones are not yet known, the intensive study of this problem, aided by detailed structural field work in many areas as yet geologically unknown, will go far toward explaining the character and mode of operation of those forces which have gone into the building of the Rocky Mountains.

[1] R. T. Chamberlin, *Jour. of Geol.*, Vol. XVIII (1910), p. 228.

[2] *Ibid.*, Vol. XXVII (1919), p. 145. [3] *Ibid.*, Vol. XXIX (1921), p. 416.

OBSERVATIONS ON THE FRESHFIELD GLACIER, CANADIAN ROCKIES

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ABSTRACT

This is a brief study of one of the large and little known glaciers of the Canadian Alps. It is nine miles long and covers an area of about 22 square miles. The surface velocity of the ice on a line across the dissipator was found to range between 3 and nearly 5 inches per day. The glacier is retreating, the amount for the past twenty years being estimated at 925 feet. A secondary tongue advances into and retreats from a small side valley intermittently and independently of the main glacier.

The comparatively recent issue by the Alberta-British Columbia Boundary Commission of the Freshfield sheet (No. 18, scale 1:62500) affords an excellent basis for observations on the Freshfield Glacier —perhaps the largest single glacier in the Canadian Rockies. It is 9 miles long, and the ice covers an area of 22 square miles (Figs. 1 and 2). Adjacent connected or nearly connected glaciers on the outer slopes of the basin bring the total area of ice in the group up to about 40 square miles.

Of a valley glacier, it is the type par excellence for this range. In simplicity of form, size, scantiness of superficial moraines, and magnificence of scenery it is unsurpassed (Fig. 3). It possesses a unique unit character, there being no real branches or separate tributaries. It may be reached with comparative ease in a journey of five days with a pack train, either from Lake Louise on the Canadian Pacific Railway, via Bow Pass, or from Field by way of the Amiskwi and Howse passes. The air-line distance from Lake Louise is about 40 miles.

The glacier occupies an oval basin in the midst of the Freshfield massif, a well-defined group of peaks about 12 miles square, situated in a semicircular loop of the continental divide between tributaries of the north Saskatchewan and Columbia rivers. Its drainage

is principally to the former. There are twenty-five peaks in the group surpassing 10,000 feet in elevation, Mount Barnard (10,955 feet) being the loftiest. Eleven of them exceed 10,500 feet. The

FIG. 1.—A portion of Sheet 18, Interprovincial Boundary Commission. Arrows show direction of ice flow.

basin is 9 miles long from southeast to northwest, and 4 miles wide. The ice discharges through a gorgelike valley to the northeast in a single tongue three-quarters of a mile wide and 3 miles long (Fig. 4).

In the summer of 1922, the writer made a brief study of the glacier during the course of a visit to the group for the purpose of ascending some of the unclimbed peaks. His two climbing companions good-naturedly assisted in the field work, and for this he is deeply grateful, as otherwise it could not have been performed. We spent eleven days at the glacier, but only three could be exclusively devoted to observations on it, so that the results presented herewith cannot claim to be more than of a preliminary and tentative nature. In the course of our five ascents, we traveled some 40 miles over the surface, and thus familiarized ourselves with nearly every part.

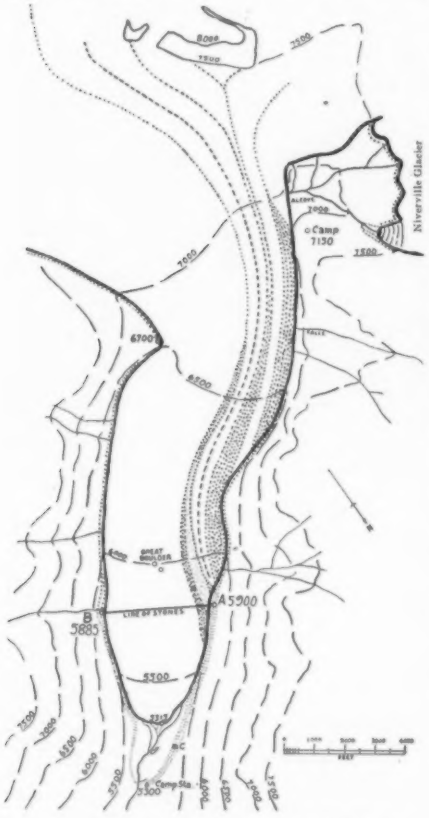

FIG. 2.—The tongue of Freshfield Glacier, showing moraines, stations, and other details, from a local survey by Howard Palmer, 1922. Adjusted to Sheet 18 of the Alberta-British Columbia Boundary Commission.

1. MEASUREMENT OF THE SURFACE VELOCITY OF THE ICE

A suitable line was selected about 1,250 yards above the end of the glacier, marked at each end by a large bowlder imbedded in the lateral moraines. These stations are designated A and B respectively on the diagram (Fig. 2).

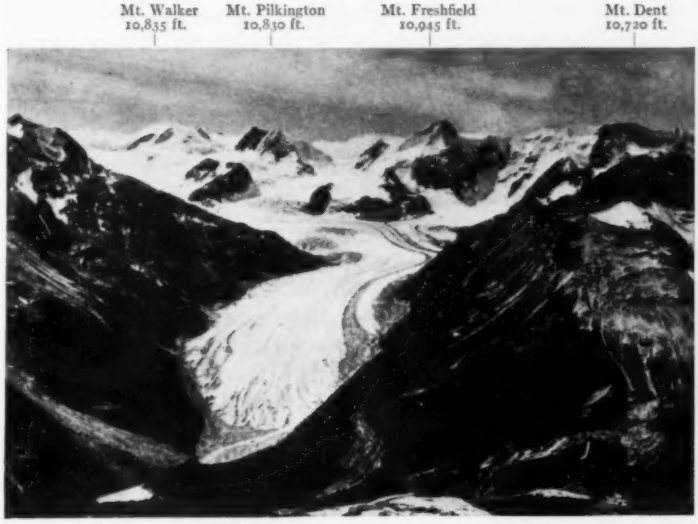

FIG. 3.—Tongue of Freshfield Glacier, from the northeast. Photograph by the Interprovincial Boundary Commission, 1918.

FIG. 4.—View down the dissipator from 7,100 feet. Photograph by H. Palmer

On July 13, station A was occupied with the instrument. Fourteen numbered flat stones were carried out on the ice and set in flat-bottomed niches, fifty paces apart, on the line indicated by the vertical hair of the telescope in accordance with signals from the observer. The azimuth and angle of depression of each stone were determined from a second station on the north moraine, later ascertained to be 320 feet distant. On the line, the ice was 1,133 yards wide.

Six days later (July 19) station A was occupied again, and the line redetermined on the ice, which had meanwhile moved downward. The amount each stone had advanced was measured directly with a tape. The results were found to range from 3 inches a day over the northerly third of the glacier, to a maximum of 4.83 inches per day at a point 900 feet from the southerly margin.

The increased average rate of flow of the southerly portion of the glacier as compared with the northerly portion is doubtless due to the fact that on the former side the ice is sweeping through a broad arc, which normally has the effect of deflecting the zone of most rapid motion away from the middle. When, as here, the curve is associated with a reversed curve farther upstream, the deflection, following the analogy of running water, naturally would be more pronounced. And so, in fact, we find it here, the zone of maximum flow being thrown far over toward the southerly margin. Actually it occurs at about one-third of the width of the glacier instead of at the center.

The weather during the period of our stay was generally warm and pleasant. A blanket of dense smoke from forest fires intensified the heat and increased the normal rate of melting, so that even in the few days of our stay the forefoot manifested a distinct slumping and retreat.

2. OBSERVATIONS ON THE TONGUE AND ITS RETREAT

It was originally intended to make a detailed photographic survey of the terminal ice tongue and the area adjacent, but this had to be abandoned on account of the density of the smoke. A local secondary triangulation, however, was carried out by the writer

from a 305-foot base, measured on the outwash moraine near camp. By this means a bowlder at the ice lip was located, which will be useful to later observers.

There is no question but that the glacier is retreating. The actual end is a thin, semicircular, concave lip, furrowed with the typical longitudinal depressions almost universally associated with this condition (Fig. 3). The frontal slope varies between 20° and 30°. As regards the rate of retreat, there seem to be no precise data available. However, the writer has been fortunate enough to obtain a photograph of the tongue, taken in 1902, which seems quite clearly to show a certain pile of moraine then in process of formation at the ice lip. Assuming this to be true, this pile of moraine, in 1922, being 925 feet distant from the most advanced ice, allows an estimate to be made of an average retreat of 46 feet per year for the twenty years intervening.

Drainage streams emerging at several points along the forefoot soon unite in a powerful torrent which cuts off the south side of the valley and prevents access to the surface of the ice except at the extreme right. Apparently the tongue does not produce a terminal ice arch or cavern.

The vertical shrinkage of the 3-mile tongue has been great. In the lower portions of the valley the most recent lateral moraines rise 100 feet or more above the ice. There is no terminal moraine, properly speaking. The tongue, as well as the upper plateau of the glacier, is singularly free from superficial moraines.

3. GENERAL FEATURES OF THE GLACIER

The main reservoir or collecting area of the glacier is a broad, fan-shaped basin with a flat floor (Fig. 5) that occupies a distorted synclinal fold on the axis of the main range of the Rockies.

The trunk glacier takes its source on the inner slopes of the southerly wall of the basin, a ridge 9,500–10,000 feet high, stretching for 6 miles between Mounts Barnard and Low (Fig. 6). Here, broad, unbroken, gently tilted inclines afford ideal conditions for glacier alimentation. In the first 3 miles the snow fields descend to 8,000 feet, where, as nearly as may be judged, the snow line

occurs (Figs. 5 and 7). The next three miles are a wide ice plain, flat and level to the eye, but really descending a thousand feet, designated on the map the "Freshfield Icefield" (Fig. 5).

FIG. 5.—Looking northwesterly across the central plateau of Freshfield Glacier from an elevation of 8,000 feet. Snow line in foreground. The alcove lies below and to the left of the small glacier tongue in the left center. Photograph by H. Palmer.

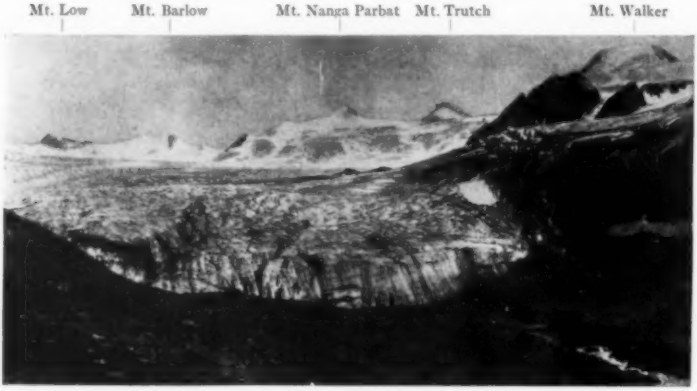

FIG. 6.—View southeasterly across the central plateau, showing intermittent lateral tongue and part of the U-shaped trough, July, 1922. Direction of principal flow is from the right toward dissipator behind slope at left. Stagnant glacier caps wall of alcove at the right. Photograph by H. Palmer.

Hereabouts the medial moraines, so prominent halfway down the tongue, begin to appear along the westerly side (Fig. 5). Rather curiously, they do not extend to the end of the tongue, as is normally

the case with glaciers of this type, but instead they run out on the side of the lobe and mingle with the north lateral moraine more than a mile above the actual ice terminus. On the diagram (Fig. 2, p. 434) they have been sketched in from photographs, giving a graphic picture of the relative importance of the tributaries as sources of ice supply.

The explanation of the phenomenon is to be sought in the vast disparity in volume between the outflow from the main reservoir and the volume contributed by the glaciers on the northerly side

FIG. 7.—The central plateau, showing the snow line and origin of the medial moraines. (Compare Fig. 6.) Photograph by H. Palmer.

of the basin (Fig. 5). Three commensal streams occur here: the Niverville and Pangman glaciers and another without a name which issues from a deep, precipitously walled cirque north of Mount Freshfield. This appears to be the most vigorous of the trio. In general, however, melting has exceeded the snow supply hereabouts, and the northerly ice sheet is in an essentially stagnant condition. The average elevation is lower, the slopes are gentler and are exposed toward the south, and the ice is thinner, all of which combine to lessen the power and volume of the discharge. It can oppose but feebly the wide current from the main reservoir to the

south, and it is therefore squeezed almost to extinction against the cliffs of the northerly valley wall (Fig. 2). At the corner where the main tongue issues from the basin, the Niverville and Pangman glaciers, in receding to the higher slopes, have uncovered a portion of the trough floor and a little upland valley, filled with rushing streams and bordered with ice tongues (Fig. 6). Thus there has been produced a lateral U-shaped alcove, across the open end of

FIG. 8.—Lateral tongue being thrust forward into U-shaped alcove. Photograph by H. Palmer.

which the main body of ice flows, exposing a section about 75 feet thick and 500 yards wide.

Such depressions are not uncommon features of valley glaciers. They often give rise to marginal lakelets, as the Marjelen See on the Aletsch Glacier in Switzerland. But this particular one possesses the peculiarity of occasionally being filled by an offshoot from the main ice field in the shape of a secondary tongue. Although at the time of our visit in 1922 it was entirely bare of ice, in July, 1918,

the Boundary Survey photographs show that it was filled to the brim with shattered ice fragments of great size. A photograph taken in August, 1913, indicates that about a year before another ice invasion had occurred here, as many wasting pillars of glacier ice were scattered about on the floor of the alcove. Thus, the place appears to serve as a kind of safety valve, which relieves pressure on the constricted dissipator whenever the snowfall on the westerly mountains has accumulated beyond the dissipator's capacity for prompt discharge.

The writer spent an afternoon visiting the locality and in photographing the ice wall at close quarters. Another secondary tongue seemed to be forming, for the wall had thrown forward several blocks of ice, a distinct nose projected at the center, and a push moraine 4 feet high had been raised along the base of the wall (Fig. 8). Another push moraine was noted 150 feet in front of the ice, apparently indicating the termination of the last advance preceding.

We thus have evidence that advances occurred here in about 1912 and 1918, and that another was being initiated for development, possibly in 1923. Can it be that this is a periodic phenomenon? It would be a very interesting matter to determine. Unfortunately, devoted observers of glaciers do not pay their respects to the Freshfield glacier with any frequency. It was only by mere chance that the photographs just referred to were secured.

But it is to be emphasized that this glacier is extraordinarily well adapted for observation. Feed for horses is ample for a long stay, and the camping place is unusually comfortable, with good water, wood, and protection in abundance. Several range lines could be set across the unusually flat surface of the dissipator, and simultaneous observations of the velocity secured. The numerous erratic blocks scattered over various portions of the surface could be mapped and a basis thus be laid for a study of their behavior during many future years. It is to be hoped that someone will take advantage of the opportunity.

EDITORIAL

Ever since the establishment of the *Journal of Geology* in 1893 its subscription price has been maintained uniformly at $4.00, as the intent has always been to keep the price as low as the cost of publication would permit. During all these years the costs of publication have been on the rise, gradually at first, then more rapidly, especially after the outbreak of the world-war. In spite of the increasing costs, however, the editors have been reluctant to increase the subscription rate. To avoid this, other means were tried. In 1919 costs were reduced by cutting the size of each number from 96 to 88 pages. This, together with a very generous contribution from one who prefers not to have his name mentioned, met the existing situation sufficiently to tide the *Journal* over a period of stress which it was hoped would be temporary. But contrary to expectation, the costs have not declined and do not show likelihood of much improvement in the immediate future. At the same time the number of articles offered for publication in the *Journal* has increased to such an extent that the reduced pages have become correspondingly inadequate.

Because of these facts, the editors have decided to restore the original size of the *Journal* and to raise the price of subscription. Beginning with the present issue, each number will therefore be on the basis of 96 pages instead of 88, and the subscription price hereafter will be $6.00 a year in place of $4.00. This will enable us to print a larger amount of material and to bring contributions out more promptly. It is hoped that readers will find in the added pages some recompense for the higher subscription rate which the editors have been obliged reluctantly to adopt.

R. T. C.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Rosenbusch, H. *Elemente der Gesteinslehre.* 4th edition, revised by A. Osann. Stuttgart: E. Schweitzerbart'sche Verlagsbuchhandlung, 1922. Pp. 779, pls. 3, figs. 115.

This standard textbook has been thoroughly revised by Professor Osann. The third edition, published in 1910, contained 692 pages and 107 figures; the fourth contains 779 pages and 115 figures, but the additional pages do not begin to indicate the changes made in the book. The Introduction, originally of 77 pages, now has 103, but it has been radically changed; much of the original material has been omitted and new matter introduced. While Professor Osann gives here an introduction to his own system of classification, it is very brief, although it might well have been expanded and definite rules for the computations might have been given.

In the special part, dealing with the rocks themselves, the definitions remain essentially as written by Rosenbusch, but new examples are given and there are many more chemical analyses, most of which are recalculated into Osann's system, and, in the case of the plutonic rocks, they are represented in triangular diagrams. There is a tendency throughout to emphasize the chemical composition, although the rock definitions retain their mineralogic significance. The descriptions of the plutonic rocks have been increased by only five pages, and of these, seven are devoted to a tabulation of the families in Osann's latest classification. This indicates the omission of considerable material from the original book, since the new diagrams and tables take up much space, but the parts omitted are nowhere extensive. There is rather a general condensation of material.

In the introduction to the "dike rocks," Osann makes clearer the Rosenbusch conception of these rocks, although even in the earlier editions it was recognized that all of the so-called dike rocks do not occur as dikes. Osann brings in Brögger's divisions of aschistic and diaschistic rocks. In the former are included Rosenbusch's granitoporphyritic dike rocks and in the latter his aplitic and lamprophyric rocks. On the whole the changes in this section are much less numerous than those among the plutonites. It is to be noted that Osann has corrected an error which appeared in all the earlier editions, namely, the texture of aplite, formerly panidiomorphic-granular, is now given as panallotriomorphic-granular. Panidiomorphic-granular, however, is still used for the texture of the various lamprophyres, also incorrectly, in the opinion of

the reviewer, although their texture in some cases approaches perhaps as nearly the panidiomorphic as it is possible for any texture. For almost complete idiomorphism, anchiidiomorphic-granular would have been better. Even idiomorphic-granular, without the pan, would be less objectionable.

Another change, which the reviewer himself made years ago in presenting the alkalic aplites to his classes, is the removal of the malchites and beerbachites from among them. Osann now places them among the lamprophyres. This makes the malchites, mineralogically, lamprophyres of the quartz-bearing diorite family. None of these rocks, according to their descriptions, differ greatly from the spessartites and odinites, although the rocks of the malchite-beerbachite series may have feldspar also among the phenocrysts, but chemically they contain much more silica and alumina and much less magnesia and lime. Originally placed by Rosenbusch among the leucocrates, although he recognized them as dark, now placed by Osann among the lamprophyres, these rocks appear to belong to neither one nor the other. They seem to be halfway between normal aschistic rocks and the lamprophyres. Osann says that many of the dark diorite dikes described in the literature are probably malchites.

The descriptions of the extrusive rocks follow essentially the form in the previous edition, although reduced by 13 pages. The divisions into older and younger eruptives are preserved, although it is recognized that this age difference is not a difference in the original character of the extrusives, but a difference due to changes, such as dynamic processes, weathering, and often thermal processes, which took place subsequent to the eruption. The older and younger rocks, as before, are liparites and quartz porphyries, trachytes and quartz-free porphyries, dacites and quartz-porphyrites, and andesites and porphyrites for the Tertiary-post-Tertiary and pre-Tertiary extrusives, and basalts, melaphyres, and diabases for Tertiary and recent, Permo-Carboniferous-Mesozoic, and earlier Paleozoic rocks.

The second part of the book, dealing with sediments, contains the same number of pages as the old edition, namely 91. The material, however, has been re-worked, and while it is essentially the same as in the old edition, in many parts the wording is different and there are additions or subtractions.

Part III, headed "Crystalline Schists" in former editions but "Metamorphic Rocks" in the new, has been increased from 105 to 147 pages, and many changes have been made so that it is practically new. The first 25 pages of this part are entirely different in the old edition, as may be seen by the new subtitles: rock metamorphism, contact metamorphism and contact metamorphosed rocks, contact metamorphism produced by extrusive rocks, and contact metamorphism produced by plutonites. After this introduction comes the section on the crystalline schists, but even this has been so thoroughly revised that it is hard to compare one book with the other. Beginning with the descriptions of the schists themselves, the differences are not so great.

In spite of the years since the death of Professor Rosenbusch, this book still remains the standard introduction to petrography, and in spite of the newer

chemical classifications, the standard old mineralogical classification still remains in use. The book will be valuable for years to come.

SCHNEIDERHÖHN, H. *Anleitung zur mikroskopischen Bestimmung und Untersuchung von Erzen und Aufbereitungsprodukten besonders im auffallenden Licht.* Berlin: Gesellschaft Deutscher Metallhütten- und Bergleute, 1922. Pp. xv+292, figs. 159, 15 folding determinative tables in pocket in back.

This textbook on the determination of ore minerals by incident light is undoubtedly of greater value to the economic geologist than to the petrographer, yet there are many things in the book that are of interest to the latter even though he be not also interested in ore deposits as such.

The book is divided into two main parts. The first or general part treats of instruments and methods of work. Hand lenses, and petrographic-, ore-preparation, and metallographic microscopes are described, and instructions are given for making observations by transmitted light and with the opaque illuminator. There are also brief descriptions of dark field illumination, microprojection-, microphotographic-, and drawing apparatus.

The next section deals with the examination of raw material, namely, grains and powders, by means of the hand lens or the preparation microscope. It gives directions for both qualitative and quantitative determinations, and for the measurement of the size of grains. The immersion method is rather fully discussed and there are directions for the preparation of thin and polished sections.

Following this is a discussion of the examination of polished sections by ordinary incident light, chalkography as it was called by Brauns, and 77 pages are devoted to the methods of observation and the phenomena observed. Under color is given a summary of Ostwald's *Die Farbnormen*, which describes the methods of observing color by means of Ostwald's color charts, and a table is given showing the colors of the various minerals as determined by its means. The etching of polished sections is taken up and the various points to be observed are noted. The first section closes with observations on polished sections by incident polarized light and a few words on microphotography.

The second part of the book, consisting of 130 pages, is devoted to the minerals themselves. Here are brought together all of the physical and optical properties of over forty ore-minerals, including their behavior under etching, their structure, and points by which they may be recognized or separated from other minerals.

The many well-made and well-photographed illustrations of thin and polished sections add greatly to the value of the book and bring out in little space and with great clearness details that would require many pages of descriptive matter.

WINCHELL, N. H. and A. N. *Elements of Optical Mineralogy.* Part I. *Principles and Methods.* Second edition. New York: John Wiley and Sons, 1922. Pp. xv+216, figs. 251.

This edition of Winchell's *Optical Mineralogy* has been entirely re-written and much enlarged by A. N. Winchell, and now differs in many respects from the first edition. An important change consists in the publication of the first or introductory part on principles and methods as a separate volume, leaving the descriptions of minerals to be published later. This change is very desirable, since the subject-matter of the two parts is so entirely different that one may wish to use one part independently of the other.

A comparison of the first edition with this one shows that the former contained 100 pages on methods, of which 23 were on crystallography and 77 relating to optics, while in the new there are 195 pages, of which 154 are on optics. The number of illustrations has been increased from 91 to 251 and the directions for laboratory work have been greatly extended. The arrangement of the material is entirely different, as may be seen from the Table of Contents: "Elementary Conceptions of Mineralogy," "Crystallography," "Physical Characters of Minerals," "Chemical Characters of Minerals," "Elementary Conceptions of Optics, Optical Properties of Isotropic Minerals, Microscopes," "Preparation of Material for Microscopic Study," "Microscopic Study of Refringence," "Isotropic Minerals," "Optical Properties of Uniaxial Minerals," "Nicol Prism," "Uniaxial Minerals in Parallel Polarized Light," "Uniaxial Minerals in Convergent Polarized Light," "Uniaxial Minerals," "Optical Properties of Biaxial Minerals," "Biaxial Minerals in Parallel Polarized Light," "Biaxial Minerals in Convergent Polarized Light," and "Biaxial Minerals."

There are practically no bibliographic references in the book, and very little mathematics has been introduced. The latter point, however, is no objection but rather an advantage in an elementary textbook. It should have a wide sale.

REVIEWS

The Occurrence of Ground Water in the United States. By O. E. MEINZER. U.S.G.S. Water Supply Paper 489, 1923. Pp. xi+321, pls. 31, figs. 110.

The great importance of ground water as a geologic agent has long been recognized. In the study of rock-forming processes, of metamorphism, and of the genesis of ore deposits, the significance of the work of ground water has received due recognition by various writers, but their conclusions have been more or less scattered through a wide range of literature. This publication is a collection in convenient form of many valuable data, together with a discussion of the principles involved.

The water-yielding capacity of a rock is measured by the amount of water which will drain into wells, and the water-retaining capacity, by the amount retained after such drainage has taken place. Expressed as percentages of the rock volume these are called respectively "specific yield" and "specific retention." The quantity of water that a saturated rock will furnish depends not on its porosity but on its specific yield. The relation of these two properties is discussed, and the various methods of determining specific yield are described.

A brief summary of the occurrence of subsurface water is given in tabular form on page 101.

"Kinds of Rock and Their Water Bearing Capacities" forms the subject of a chapter, as does also "The Structure of Rocks and Its Influence on Ground Water." The water bearing formations of the United States are described in chronological order.

A. H. B.

Report of the State Geologist of Vermont, 1921–1922. By GEORGE H. PERKINS. Burlington, Vt., 1923. Pp. x+342, pls. 24.

The author presents a summary of the more important work accomplished by the Vermont Geological Survey from the time of its inception in 1844 until 1922. This is followed by a series of five articles by geologists from adjoining states who have investigated problems in Vermont geology of more or less general interest. Among these may be mentioned: (1) a detailed study of some of the Ordovician rocks of the Champlain Valley, by E. J. Foyles; and (2) a study of some of the faults of the Champlain Valley, by G. H. Hudson.

A. H. B.

The Geology of the Country round Banff, Huntly and Turriff. By H. H. READ. Memoirs of the Geological Survey, Scotland, 86 and 96. Edinburgh, 1923. Pp. 240, figs. 11.

The Highland schists, consisting of metamorphosed sediments, are the oldest and most widespread rocks of the district. Previous to the main development of the schistosity, the Highland schists were intruded by a varied series of igneous rocks, chiefly basic, called the Older Igneous Rocks. A later series, the Younger Igneous Rocks, provide excellent examples of *contamination*, here used to mean the modification produced in an igneous magma by the absorption of sedimentary material. The magmas affected were of noritic or gabbroic character. Besides the normal minerals of the gabbros, the contaminated rocks contain biotite, quartz, orthoclase, microcline, andesine, garnet, tourmaline, silliminate, spinel, and, most likely, corundum. Chemically they are characterized by an abnormal percentage of alumina and a great decrease in lime and magnesia. Contact metamorphic effects due to the igneous intrusions are important and widespread. The intrusion of the Younger Igneous Rocks was complete before the deposition of the Middle Old Red Sandstone of this area.

A feature of interest to petrologists is the inclusion of about forty new chemical analyses.

A. H. B.

Palaeozoic and Mesozoic Seas in Australasia. By W. N. BENSON. Transactions of the New Zealand Institute, Volume LIV, 1923. Pp. 62, figs. 11.

The author summarizes existing knowledge of the geologic history of Australasia, with special reference to sedimentation, the succession of faunas, and diastrophic movements. He compares the older with the more modern views concerning the age of the various geologic formations in Australia and New Zealand, adopting the European time scale as a standard of reference. His latest interpretations of the relations of ancient seas and lands are set forth graphically in a series of eleven paleogeographic maps from Pre-Cambrian to Upper Cretaceous times.

For the student who wishes to compare earth history in widely separated portions of the globe the article is of unusual interest and value.

A. H. B.